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Assessment of Radar Data Quality in Upland Catchments
Supplementary Report
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Summary

The corrections applied to radar data to account for the low-level orographic enhancement process have been found to have a critical impact on radar data quality across upland areas. The performance of an orographic correction scheme based on the physical model of orographic enhancement developed by Alpert and Shafir (1989) is compared with the current operational method based on the climatology of Hill (1983).

Analysis of corrected radar data and surface gauge rainfall measurements shows that the Alpert and Shafir (1989) model implementation considered generates realistic orographic enhancements across windward slope regions in the upland areas considered. This results in comparable performance of radar data corrected using the Alpert and Shafir (1989) enhancements and with the current operational method at these locations. Case study evidence shows that a physical modelling approach may provide particular benefit to radar data quality in regions where the climatology currently applied as part of the operational processing chain does not consistently represent all cases. In contrast, considerable under-estimation of radar-derived surface rainfall rates is observed within valley locations downwind of mountain ranges where the implementation of the Alpert and Shafir (1989) model considered predicts very small enhancements but gauge data show significant orographic enhancement. Improvements to the implementation of the Alpert and Shafir (1989) model are therefore required before use of the computed enhancements to correct the operational radar data can be considered in place of the current method.

The horizontal resolution of the terrain model used to compute the orographic enhancements is found to be the most important factor affecting the results of the Alpert and Shafir (1989) model. The poor radar data quality downwind of mountain ranges achieved using corrections derived from the Alpert and Shafir (1989) model results from the model considered being applied to coarse resolution terrain data. The use of higher-resolution terrain data is found to generate larger orographic corrections across broader geographical areas. Sensitivity tests also show that the results of the Alpert and Shafir (1989) model can be altered considerably by varying the tuning parameters used.

1 Background

The Assessment of Radar Data Quality in Upland Catchments project aimed to quantify the uncertainties in radar measurements provided by the current operational radar processing chain for three upland regions of contrasting terrain and radar coverage. This was achieved by comparing radar-derived surface rainfall data with surface gauge measurements across the Upper Exe, Upper Conwy and Upper Taff regions during a year-long study period between July 2005 and June 2006. The analysis and results are discussed in the project Final Report.

The main findings of the study are listed below:

- The quantitative accuracy of radar data at long range over hills is currently worse than over lowland areas.
- Range from the radar is the most important factor affecting radar data quality across upland areas.
- The impact of applying orographic corrections to the background radar data was found to be most beneficial for measurements across the Upper Conwy region, where coverage is provided by radars at over 100 km range. The orographic corrections led to improved agreement between radar and gauge data by typically 56%.
- For the highest gauges in the Upper Conwy and Upper Taff regions, the orographic corrections were still found to be insufficient to fully correct for a general underestimation of surface rainfall. In these cases, the corrected radar data typically underestimate the observed surface rainfall by 50%.
- Radar data quality is highly variable between different events characterised by orographic effects and between different gauge locations within each region for a given event.
- Almost all of the spatial variation of the radar data across the Upper Conwy region resulted from the addition of orographic corrections, with radar measurement typically detecting only whether any rainfall was present across the region.
- The radars were unable to capture small-scale features such as short-lived localised rainfall peaks associated with embedded convection in the Upper Conwy and Upper Taff regions.
- Least consistent behaviour during case study events was observed for radar data across the Upper Taff region, where the impact of orographic corrections was found to be particularly variable.
- Radar data quality over upland areas is currently of insufficient quality for quantitative use in flood forecasting. Although the application of spatially and temporally varying orographic corrections was identified as having considerable benefit to these data, analysis of total rainfall accumulations during rainfall events has shown that typically only 50% of events when in excess of 30 mm was recorded by surface gauges would have been detected as exceeding that threshold using the available radar data alone.
- Improvements to the radar data processing are likely to contribute most significantly to improving flood forecasting in upland areas. The quantitative accuracy of radar measurements in upland areas has been found to critically depend on the orographic corrections applied to the available background data, particularly in those upland regions where radar coverage is only available at ranges in excess of 50 km.
- The dependence of the orographic corrections applied across England and Wales on climatology has been identified as a potential limitation, and it is thought that adoption of a physical modelling approach across the entire radar domain may improve quantitative accuracy of the radar system.

- An assessment of the likely impact of improving the radar coverage across north Wales has suggested that there is little to be gained for flood warning and forecasting needs from such a development before radar performance is improved, particularly given the practical limitations on suitable locations for additional radars in the region.

The study found that the corrections applied to radar data across upland areas to account for the low-level rainfall enhancement process have a critical impact on data quality. Long-term statistical measures of data quality and analysis of specific case study periods showed that the current orographic correction scheme is successful in improving the agreement between background radar and surface gauge rainfall measurements across the upland regions of England and Wales considered. The case studies also highlighted periods when the corrections applied were insufficient to fully correct the measured radar data to match the observed surface rainfall and other periods when the applied corrections led to considerable overestimates of surface rainfall by the radar. In light of these results, there is clearly scope for improving the current orographic enhancement scheme. Further, the developments in the numerical models used as input to the correction scheme which have taken place since the orographic correction processing was first implemented provide opportunities to use additional information to derive the correction fields.

The orographic correction scheme currently applied to radar data over England and Wales is based on the climatology of orographic enhancement developed by Hill (1983) while the physical model developed by Alpert and Shafir (1989), referred to as AS89 hereafter, is applied to radar data across all other regions across the radar network. One of the principle recommendations made by the Assessment of Radar Data Quality in Upland Catchments project was to investigate the relative benefits of applying orographic corrections derived using the AS89 model compared with the climatology of Hill (1983). The envisaged advantages of using such a physically-based approach to compute the orographic enhancement fields are discussed in the project Final Report and listed below.

- Consistency between correction fields applied across the radar network domain,
- Corrections can be defined at improved spatial resolution,
- Corrections can make use of additional model parameters,
- Corrections can be computed in real-time rather using values from pre-defined fields,
- Corrections can be easily modified in light of future processing or model developments.

This supplementary study provides an initial comparison of the two approaches. The main aim of this study is to characterise the performance of the AS89 method in correcting radar data over each of the three upland regions considered during the Assessment of Radar Data Quality in Upland Catchments project. The outcome will inform whether the proposed Upland Catchments Implementation project should aim to derive and implement a best-tuned version of the AS89 method applied at the most appropriate horizontal resolution, or whether investigation of using a different approach to computing the orographic corrections is required.

2 Orographic correction methods

The current operational processing of radar data conducted by the Met Office involves adding a correction to the derived background surface rain rate to account for the orographic enhancement of low-level rainfall over hills and mountains. The magnitude and distribution of the corrections applied is currently computed as part of the NIMROD nowcasting system and depends on the humidity, wind speed and wind direction at the 800 m level in the operational mesoscale model. The orographic correction added at each pixel is obtained from fixed enhancement fields, based on the observed climatology of Hill (1983) across England and Wales and the AS89 model across all other parts of the radar domain. Different fields are defined for each combination of 9 different wind direction and 4 wind speed categories. No correction is applied if the model relative humidity value is less than 85% or for wind speeds of less than 8 ms^{-1}. Further details are provided in the Assessment of Radar Data Quality in Upland Catchments project Final Report.

The AS89 method assumes that the orographic enhancement of rainfall can be equated to the moisture convergence caused by uplift due to hills and mountains. Assuming that a constant boundary layer depth Z_s follows the orography, the net contribution to the precipitation induced by the local terrain at each point is expressed as,

$$P' \approx \frac{\varepsilon r e_S(Z_s) V \cdot \nabla Z_S}{R_d T(Z_S)}$$

where $\varepsilon = R_v / R_d$ is the ratio of gas constants for water vapour and dry air and r, e_s and T are the relative humidity, saturation vapour pressure and temperature respectively. The product $V.\nabla Z_s$ approximates the vertical velocity contribution from orographically forced convergence where V is the horizontal velocity at the top of the boundary layer and ∇Z_s is the given by the local terrain slope. The local enhancement on downwind slopes where ∇Z_s is negative is set to 0. The effect of advection is accounted for in the model by estimating the area averaged orographic enhancement at a given point to be a weighted sum of the upwind local enhancements P' as,

$$P_0 = f \frac{1}{W_0} \sum_{i=0}^{N} W_i P_i'$$

where f is an empirically derived efficiency factor. The sum is computed over the N upwind points contributing to the orographic enhancement at a point x_0 where W_0 is the total sum of the weights W_i which are expressed for each upwind point i as

$$W_i = e^{-(x_i - x_0)^2 / 2\sigma^2}$$

The weighting function scales with the typical downwind distance travelled by a cloud, $\sigma = |V|.t$, where t is a tuneable parameter representing the typical lifetime of a precipitating cloud.

The orographic correction fields used in this study to investigate the impact of applying the AS89 physical model are computed using the formulation currently implemented as part of the recently developed STEPS nowcasting system. There are several differences between the implementation of the AS89 model to compute orographic corrections in STEPS and NIMROD, summarised in Table 2.1. The NIMROD implementation uses the AS89 model to compute a number of static enhancement fields for each of the wind speed and wind direction classes defined by the climatology of Hill (1983). Orographic corrections are then computed in real-time by selecting the appropriate correction field for the given wind conditions and scaling values by the model relative humidity to account for the variation of the AS89 results with humidity. In contrast, the STEPS implementation computes corrections by applying the AS89 model in real-time using the available

model-derived wind, temperature and relative humidity data. The STEPS implementation uses higher-resolution model data derived from the recently developed UK 4km mesoscale model. The terrain slopes along the local wind direction are computed for each hourly model run in the STEPS system using terrain data with a 2 km horizontal resolution. This is considerably coarser than the terrain used to compute the static correction fields used by NIMROD. Note that a scaling factor of 0.6 was applied to wind speeds in the implementation of AS89 in NIMROD to replicate the distribution of enhancements produced by the Hill (1983) method. This scaling factor has since been preserved in the implementation of the scheme in STEPS. Sample enhancement fields are shown in Figure 2.1.

	NIMROD – *current operational scheme*	STEPS – *example implementation of AS89*
Orographic correction type	Scaled values from discrete correction fields	Continuous correction values
Mesoscale model data input	North Atlantic European model	UK 4km model
Horizontal resolution of model data	5 km (scaled from 12 km)	2 km (scaled from 4 km)
Boundary-layer height	800 m	900 m
Terrain resolution	500 m	2000 m
Minimum humidity for correction	85%	80%
Minimum wind speed for correction	8 ms-1	> 0 ms-1
Efficiency factor *f*	0.15	0.15
Cloud lifetime *t*	170 s	170 s
Maximum upwind fetch	15 km	15 km
Velocity scaling factor	0.6	0.6

Table 2.1: Summary of characteristics of the Alpert and Shafir (1989) orographic enhancement model implementations in the NIMROD and STEPS nowcasting systems.

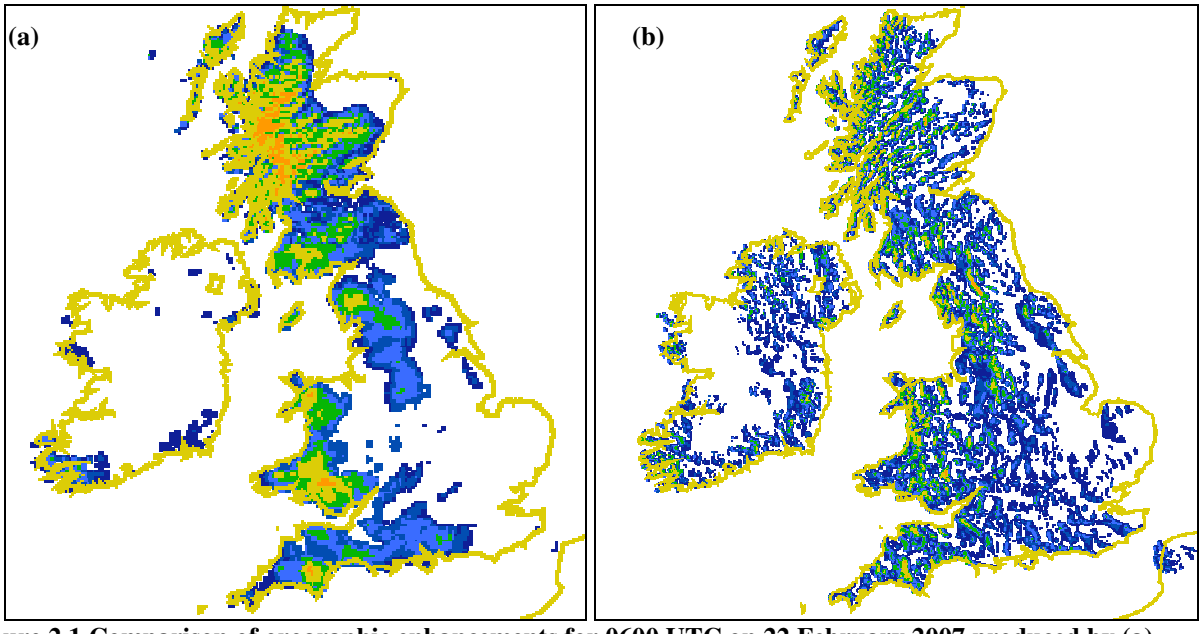


Figure 2.1 Comparison of orographic enhancements for 0600 UTC on 22 February 2007 produced by (a) NIMROD and (b) STEPS nowcasting systems.

3 Data analysis

This study has been motivated by the investigations conducted as part of the Assessment of Radar Data Quality in Upland Catchments project. Radar data were compared with measurements of surface rainfall from several rain gauges in each of the Upper Exe, Upper Conwy and Upper Taff study areas. The Upper Exe region in North Devon was considered to be a region of good radar coverage. Rainfall data are available across the region at 1 km horizontal resolution from the Cobbacombe Cross radar, located about 30 km to the south-east. In contrast, the Upper Conwy region in North Wales was considered to be a region of relatively poor radar coverage. Rainfall data are only available at 5 km resolution from radars located at ranges of over 100 km at Clee Hill, Crug-y-Gorllwyn and Hameldon Hill. Radar coverage across the Upper Taff region in South Wales is available at a 2 km horizontal resolution from the two radars located at Clee Hill and Crug-y-Gorllwyn. Radar and gauge data measured between 1 July 2005 and 30 June 2006 were archived specifically for the study.

The impact of applying the AS89 model to compute orographic corrections on radar data quality is investigated in this study using a similar comparison of radar and rain gauge measurements of surface rainfall in each of the three upland regions identified. The rain gauge data are assumed to represent the 'ground truth' of surface rainfall against which the radar data are assessed. Re-analysis of the data archived between July 2005 and June 2006 is not practical as more recent developments to the UK 4km model may make comparison of the two correction schemes using archived model data unrepresentative of current or future performance. As such, summary statistics and case study analyses are presented using available data measured over a 14 day period between 21 February and 7 March 2007. This period was characterised by prolonged rainfall in each of the upland regions of interest, with over 100 hours associated with rainfall recorded at each gauge location considered. The radar data are compared with the hourly rainfall accumulations measured by surface gauges which are routinely archived as part of the radar processing system for real-time comparisons. The available gauge locations in each study area are listed in Table 3.1.

Study area	Site Name	Easting	Northing	Altitude (m)
Upper Exe	Liscombe [LS]	287400	133200	348
	Brendon Hill [BH]	292705	137905	386
Upper Conwy	Capel Curig [CC]	270100	357000	216
Upper Taff	Sennybridge [SB]	289400	241700	189
	Llyn-y-Fan [LL]	279700	223800	264

Table 3.1a: Details of available rain gauges in the Upper Exe, Upper Conwy and Upper Taff study areas.

	Cobbacombe		Crug-y-G		Clee Hill		Predannack	
	Range (km)	Beam height	Range (km)	Beam height	Range (km)	Beam height	Range (km)	Beam height
Liscombe [LS]	17	122	115	1777	161	2290	166	2827
Brendon Hill [BH]	18	102	113	1709	155	2107	173	2993
Capel Curig [CC]	-	-	129	2219	118	1563	-	-
Sennybridge [SB]	-	-	58	854	79	982	-	-
Llyn-y-Fan [LL]	-	-	49	643	96	1150	-	-

Table 3.1b: Range of available radars from each rain gauge and typical height above the surface (in m) of the lowest usable radar scan at each gauge location.

As in the Assessment of Radar Data Quality in Upland Catchments project, timeseries of "background" and "corrected" radar data are considered. The background data are the radar-derived surface rainfall estimates produced by the VPR correction process with no orographic correction applied. The corrected data have undergone additional orographic corrections and have been calibrated against surface rain gauges to correct for mean biases by applying a radar-dependent gauge adjustment factor (GAF). The background and corrected radar timeseries are related as,

$$CORRECTED = GAF.(BACKGROUND + OROG)$$

Given archived timeseries of the background and corrected radar data produced operationally and of the orographic enhancements predicted by the NIMROD and STEPS nowcasting systems, it is possible to assess the relative impact of the current orographic correction scheme and the AS89 approach. Radar data corrected using the current operational orographic correction scheme are labelled 'NIMROD' as the corrections applied have been derived as part of the NIMROD nowcasting system.

$$NIMROD' = GAF.(BACKGROUND + OROG_NIMROD)$$

The NIMROD results are to be compared with radar data corrected with enhancements derived using the AS89 model implemented in the STEPS nowcasting system, labelled 'STEPS'.

$$STEPS' = GAF.(BACKGROUND + OROG_STEPS)$$

The magnitude of the orographic correction applied to the background surface rainfall estimate can be capped during the operational processing if the corrections are considered to be too large. This occurs when the background rainfall rate is less than 1/32 mmh^{-1} and the background rate is then scaled by a factor of less than 1. In order to compare the two orographic correction schemes, the proportion of the STEPS-derived orographic correction applied to background radar data is the same as the proportion of the NIMROD-derived correction applied to radar data during the operational processing chain. In these circumstances the rainfall data to be compared with the operationally corrected values is,

$$STEPS = [GAF.(BACKGROUND + OROG_STEPS)]xSCALE$$

where *SCALE* is the ratio between the rainfall value derived operationally and the rainfall expected if all of the NIMROD-derived enhancement were applied.

$$SCALE = CORRECTED / [GAF.(BACKGROUND + OROG_NIMROD)]$$

4 Radar data quality overview

The correlation between radar and gauge measurements of surface rainfall at each available gauge location across the Upper Exe, Upper Taff and Upper Conwy regions is plotted in Figures 4.1, 4.2 and 4.3 respectively. The gauge measurements are compared with hourly rainfall accumulations of the background radar data and radar data corrected with orographic enhancements computed using the current operational method (labelled NIMROD) and the STEPS implementation of the AS89 physical model (labelled STEPS). The level of agreement between the gauge and radar data in each case is summarised by calculating the root mean square factor (RMSF) value of those timeseries. Further details are provided in the Assessment of Radar Data Quality in Upland Catchments project Final Report. Only data from time periods when both gauge and radar accumulations show greater than 0.0 mm are considered in the calculation of the RMSF value. Perfect agreement between the gauge and radar measurements would correspond to an RMSF value of 1.0. These statistics are listed in Figures 4.1, 4.2 and 4.3.

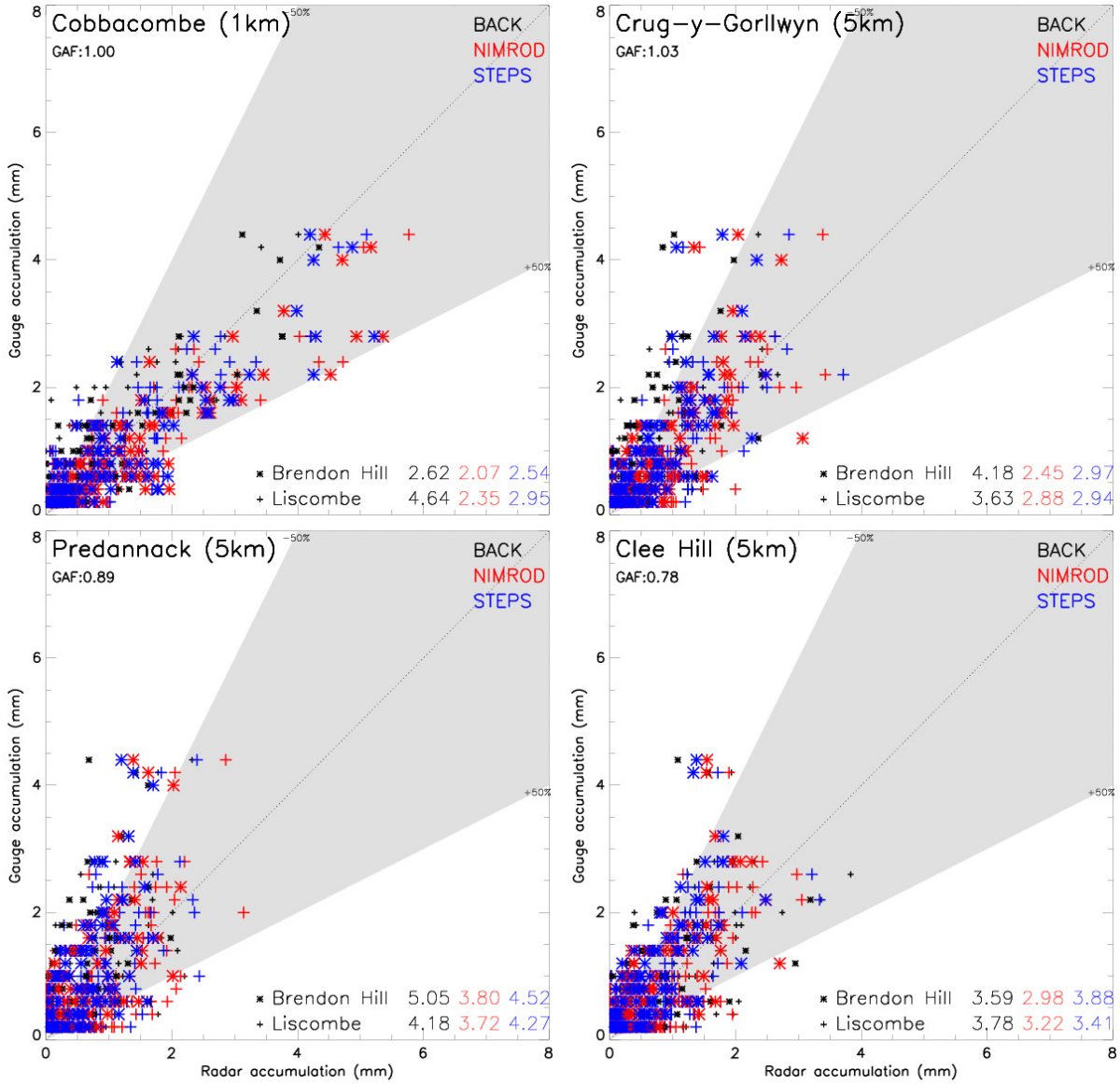


Figure 4.1: Correlation between hourly gauge accumulations in the Upper Exe study area and background (black), NIMROD-corrected (red) and STEPS-corrected (blue) radar data from (a) Cobbacombe Cross, (b) Crug-y-Gorllwyn, (c) Clee Hill and (d) Predannack radars. Summary RMSF statistics are listed on each plot.

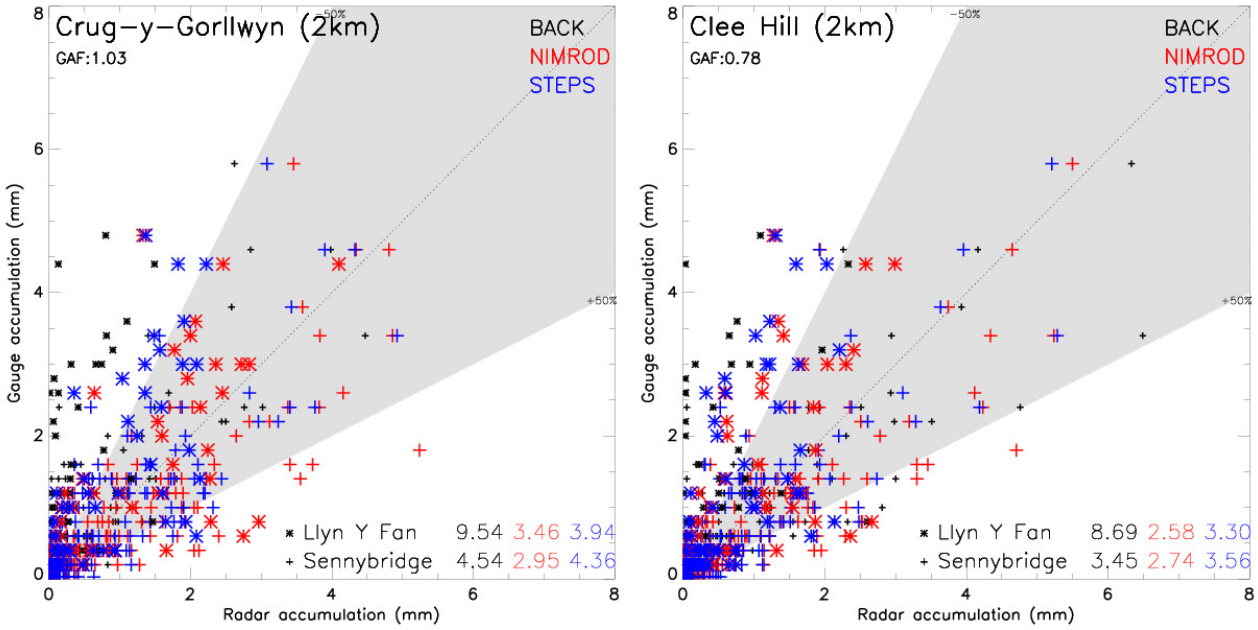


Figure 4.2: Correlation between hourly gauge accumulations in the Upper Taff study area and background (black), NIMROD-corrected (red) and STEPS-corrected (blue) radar data from (a) Crug-y-Gorllwyn and (b) Clee Hill radars. Summary RMSF statistics are listed on each plot.

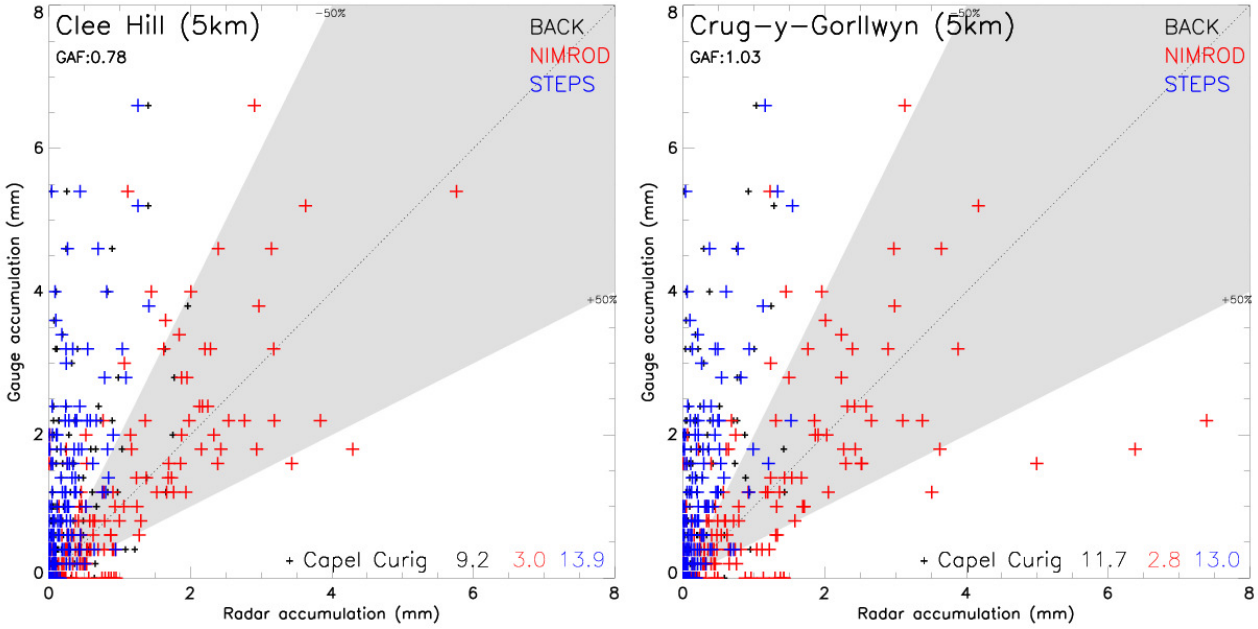


Figure 4.3: Correlation between hourly gauge accumulations in the Upper Conwy study area and background (black), NIMROD-corrected (red) and STEPS-corrected (blue) radar data from (a) Clee Hill and (b) Crug-y-Gorllwyn radars. Summary RMSF statistics are listed on each plot.

Figures 4.1 and 4.2 show improved agreement between gauge and corrected radar data than between gauge and background radar data in the Upper Exe and Upper Taff regions. This is consistent with the results of the Assessment of Radar Data Quality in Upland Catchments project, demonstrating that the application of orographic corrections to radar data to have a beneficial impact on data quality. The hourly accumulations computed for radar data corrected using the STEPS implementation of the AS89 model are comparable with the radar data corrected using the current operational NIMROD orographic correction scheme. In all cases, the RMSF value computed for the STEPS data is greater than the corresponding NIMROD value however. This

suggests that while the AS89 approach would be a potentially useful method to compute orographic corrections and improve radar data quality over upland areas, the current operational orographic correction scheme produces more realistic enhancements than the STEPS implementation of the AS89 model. Improvements to the AS89 model results would be required before use of the computed enhancements to correct the operational radar data can be considered.

In contrast, Figure 4.3 shows stark differences between the correlation of gauge and corrected radar data using the NIMROD and STEPS orographic enhancement fields. While the NIMROD-derived corrections lead to considerable improvement between the gauge and radar rainfall accumulations, the STEPS-derived corrections are generally small and make little difference to the background radar data. Figure 4.3 shows consistent under-estimation of the gauge-measured surface rainfall by the STEPS-corrected radar data by typically 90%. This illustrates a clear failing of the STEPS implementation of the AS89 orographic enhancement model in this region. As identified in the Assessment of Radar Data Quality in Upland Catchments project, Figure 4.3 shows generally small background radar-derived rainfall values, independent of the rainfall totals measured by the Capel Curig gauge. This is because the radars with coverage across the region are at long range and only reliably detect the presence of rainfall. The quantitative accuracy of the derived surface rainfall estimate is therefore critically dependent on the application of representative orographic enhancements. The RMSF statistics listed in Figure 4.3 show the application of the STEPS-derived corrections to have a detrimental impact on radar data quality, with corrected RMSF values in excess of the value computed for background radar data. This is because the gauge adjustment scaling applied to both datasets is strictly only relevant to the radar data corrected using the operational NIMROD orographic enhancement scheme.

Case study analysis is required to understand the reasons for the poor performance observed in the Upper Conwy region and to identify the developments which may be required to produce more representative corrections across all upland regions. Comparable performance of the AS89 corrections with the current operational method in the Upper Exe and Upper Taff regions suggests that there is some merit in developing this approach but clearly the errors evident from measurements in the Upper Conwy region need to be addressed before further development work and implementation of a revised correction scheme can be considered.

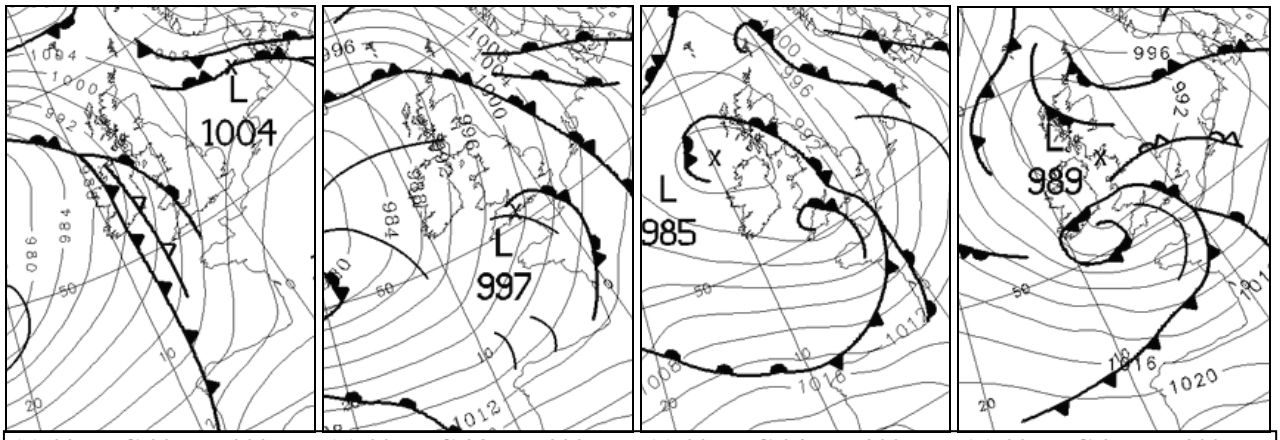
21-26 February 2007

February 2007 was characterised by generally above average rainfall, with the monthly rainfall over England and Wales about 130% of the long-term average value for example. A period of persistent rainfall during the last week of February brought plentiful rainfall to each of the study areas considered. The total rainfall measured by each available surface gauge during this period is listed in Table 5.1.

Upper Exe		Upper Conwy		Upper Taff	
Gauge	Accum.	Gauge	Accum.	Gauge	Accum.
Liscombe	32.4 mm	Capel Curig	74.6 mm	Sennybridge	42.1 mm
Brendon Hill	37.6 mm			Llyn-y-Fan	66.0 mm

Table 5.1: Rainfall accumulations at available gauges in the three upland study areas over a 5-day period between 21 and 26 February 2007 inclusively.

Figure 5.1 illustrates a series of fronts associated with a deep Atlantic depression crossing the British Isles from the west which brought periods of prolonged rainfall and heavy showers to most regions between 21 and 26 February.



(a) 00 UTC 22 Feb 2007 **(b) 00 UTC 23 Feb 2007** **(c) 00 UTC 24 Feb 2007** **(d) 00 UTC 25 Feb 2007**

Figure 5.1: Surface pressure analysis charts for 0000 UTC during rainfall period on 22-25 February 2007.

The 2 km resolution fields derived from the UK 4km mesoscale model output for 0600 UTC are plotted in Figure 4.2. These model fields were used to derive the STEPS orographic correction field shown in Figure 2.1(b). The results show moderate south-westerly boundary layer winds across southern parts of the UK with wind speeds of about 15 ms^{-1}. Relative humidity values in excess of 90% lead to orographic corrections being computed across western parts of the UK in Figure 2.1.

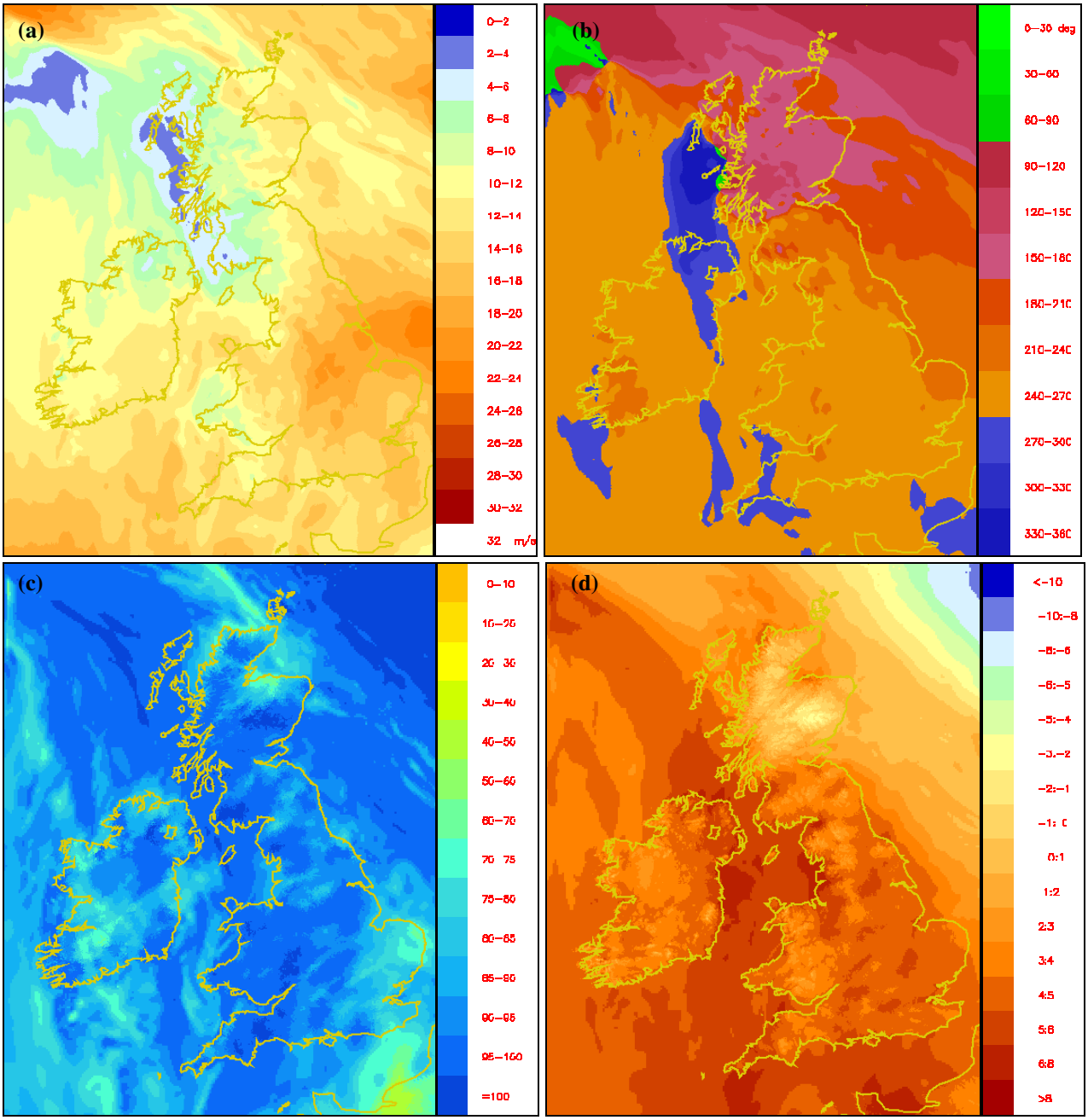


Figure 5.2: Met Office UK 4 km model fields for 0600 UTC on 22 February 2007 showing (a) wind speed, (b) wind direction, (c) relative humidity and (d) temperature at the 900 m level used to derive the orographic corrections shown in Figure 2.1.

5.1 Upper Exe

Figure 5.3 shows timeseries of hourly rainfall accumulations measured over a 48 hour period by the available gauges in the Upper Exe region. The rainfall is associated with the passage of the warm and cold fronts illustrated in Figure 5.1(a). Timeseries of hourly rainfall accumulations derived from measurements by those radars with coverage at each gauge location are also plotted. Background radar data are plotted as dashed lines. The corrected data with orographic enhancements computed using the current operational method (labelled NIMROD) and an implementation of the AS89 approach (labelled STEPS) applied are shown separately.

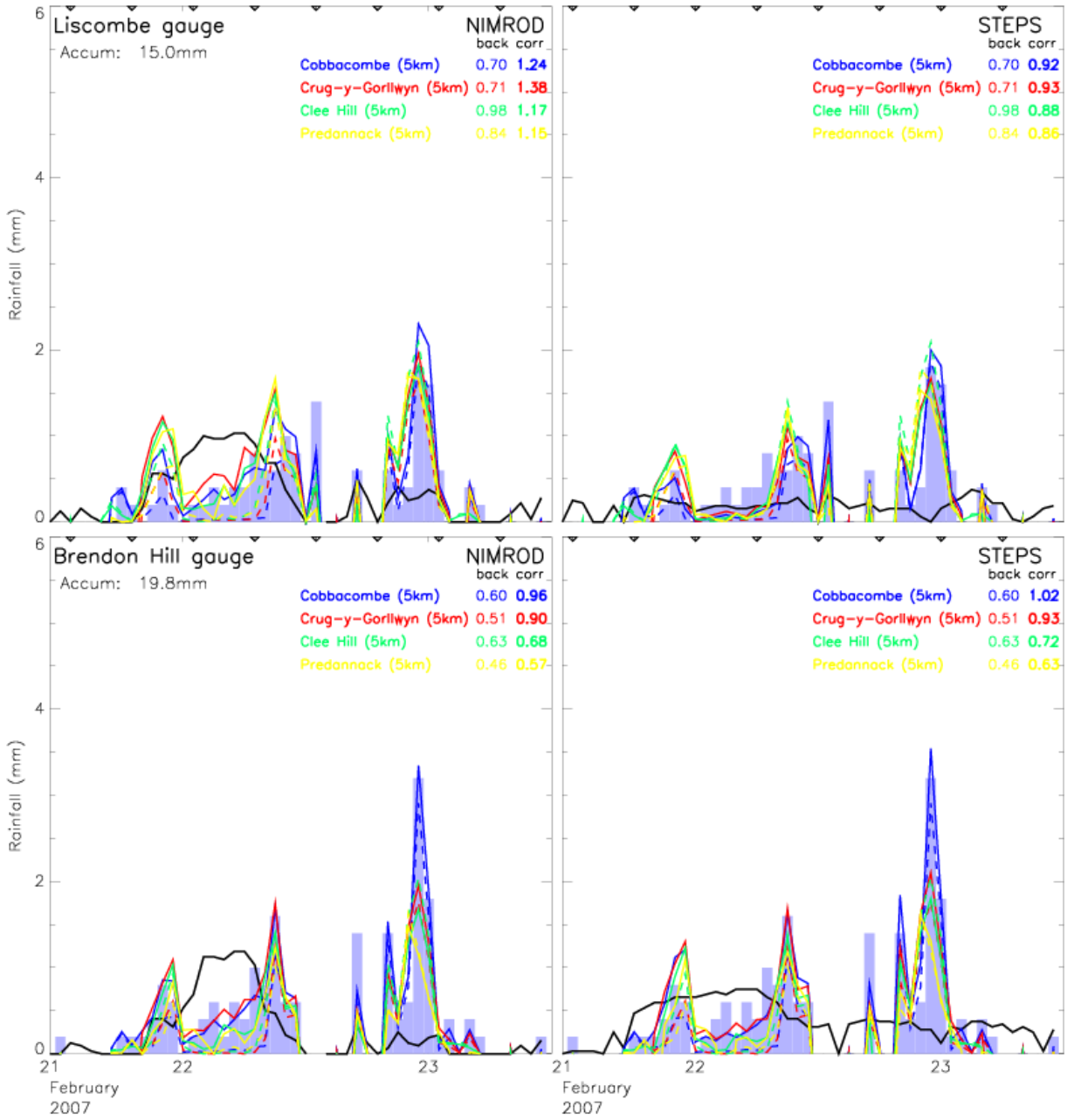


Figure 5.3: Timeseries of hourly rain gauge measurements (bars) and background (---) and corrected (—) radar measurements for the closest pixel to Liscombe and Brendon Hill gauges between 1200 UTC on 21 and 23 February 2007. The total rainfall accumulation for each gauge is listed along with the ratio of total radar to gauge accumulations for each radar (corrected values in bold). Results are shown separately for corrected data using NIMROD and STEPS orographic enhancement fields. The orographic correction is plotted in black. Periods when the orographic correction exceeds the corrected radar data result from capping (Section 2).

The level of agreement between the gauge and radar rainfall measurements in the Upper Exe region during the period shown in Figure 5.3 is similar for radar data corrected using orographic enhancements computed by both the climatology (NIMROD) and AS89 (STEPS) approaches. In both cases, the application of orographic corrections has a beneficial impact on data quality, reducing the general underestimate of surface rainfall by the background radar-derived estimates. For both gauge locations, the best overall agreement between the gauge and radar-derived rainfall accumulations is achieved using the STEPS corrections. At Liscombe, the NIMROD scheme leads to radar data from the closest radar at Cobbacombe over-estimating surface rainfall by 24% while

STEPS corrections lead to an 8% under-estimate. At Brendon Hill, the NIMROD scheme produced slightly under-estimated rainfall values, which were improved by applying the STEPS scheme. Figure 5.3 shows that similar behaviour occurred for all radars with coverage across the region. This evidence suggests that the AS89 approach is a valid method for computing representative orographic enhancement.

The period of greatest interest during the event occurred between 0000 UTC and 0900 UTC on 22 February 2007, when background rainfall estimates from all radars were generally small but the gauge data show considerable accumulations. This behaviour is consistent with the orographic enhancement process with the radar beams sampling a region of less intense rainfall aloft and overshooting the low-level region of more intense rainfall near the surface. The orographic enhancement fields used to correct radar data during the hour after 0600 UTC on 22 February 2007 are illustrated in Figure 5.4. Note that the timeseries in Figure 5.3 show that the magnitude of the orographic correction applied were capped during this period due to the small background rainfall values detected. Further details were provided in Section 2. The STEPS field plotted in Figure 5.4 clearly shows more localised features than the NIMROD field, with corrections ranging from a maximum of 4.3 mmh^{-1} over windward slopes on the western edge of Exmoor to 0 mmh^{-1} within some valleys and along the North Devon coast. This detail has a particular impact on the corrections applied to radar data at the two available gauge sites located to the south-east of the region. Figure 5.3 shows that the STEPS corrections applied at Liscombe were generally lower than NIMROD corrections throughout the period considered. For example, at 0600 UTC (Figure 5.4) the STEPS correction applied at Liscombe of 0.1875 mmh^{-1} was 5 times smaller than the corresponding NIMROD value. The AS89 model considers Liscombe to be in a rain shadow region downwind of the western ridges on Exmoor while the climatology of Hill (1983) suggests that rainfall over most of the Exmoor region was be subject to moderate orographic enhancement. The results plotted in Figure 5.3 show good agreement between the NIMROD-corrected radar and gauge data during this period at both Brendon Hill and Liscombe while the reduced orographic enhancements estimated by STEPS led to generally under-estimated STEPS-corrected rainfall values. Table 5.1 lists sample hourly gauge and radar rainfall accumulations between 0600 UTC and 0700 UTC on 22 February 2007.

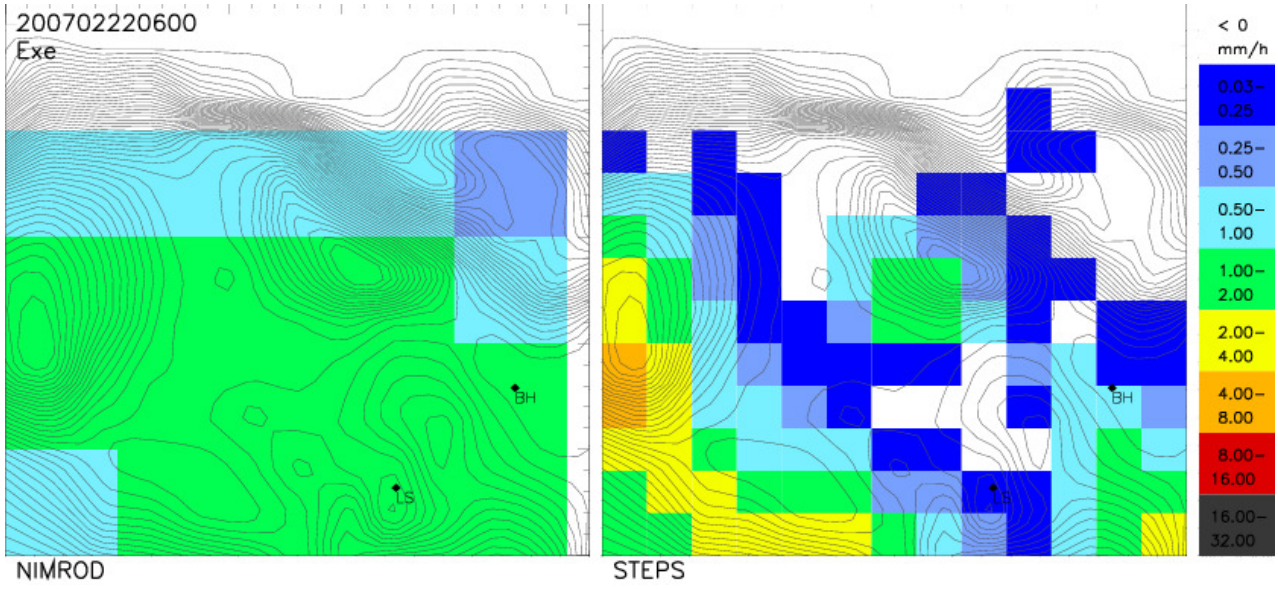


Figure 5.4: Orographic correction fields computed using NIMROD and STEPS methods to be applied to radar data across the Upper Exe region at 0600 UTC on 22 February 2007. The location of the Brendon Hill and Liscombe rain gauges are marked and labelled BH and LS respectively.

Gauge		Radar	Back	NIMROD		STEPS	
				Orog	Corr	Orog	Corr
Liscombe	0.40 mm	Cobbacombe (1 km)	0.04	1.03	0.74	0.19	0.16
		Cobbacombe (2 km)	0.03		0.49		0.10
		Cobbacombe (5 km)	0.03		0.55		0.11
		Crug-y-Gorllwyn (5km)	0.03		0.86		0.18
		Clee Hill (5 km)	0.07		0.62		0.15
		Predannack (5 km)	0.07		0.37		0.09
Brendon Hill	0.40 mm	Cobbacombe (1 km)	0.23	1.19	0.76	0.75	0.53
		Cobbacombe (2 km)	0.03		0.57		0.37
		Cobbacombe (5 km)	0.03		0.50		0.32
		Crug-y-Gorllwyn (5km)	0.03		0.63		0.40
		Clee Hill (5 km)	0.07		0.23		0.14
		Predannack (5 km)	0.07		0.12		0.08

Table 5.1: Comparison between background and corrected radar hourly accumulations (in mm) between 0600 and 0700 UTC on 22 February 2007 and gauge measured hourly accumulations at Liscombe and Brendon Hill.

Radar data quality during the rest of the event after 1200 UTC on 23 February 2007 was generally similar using the NIMROD and STEPS orographic correction schemes. Rainfall estimates derived from radar measurements at Cobbacombe Cross generally over-estimated gauge values while estimates from the other radars at longer range under-estimated rainfall by up to 40%. Orographic enhancement was generally insignificant during this period. Figure 5.5 illustrates the rainfall timeseries measured at Liscombe.

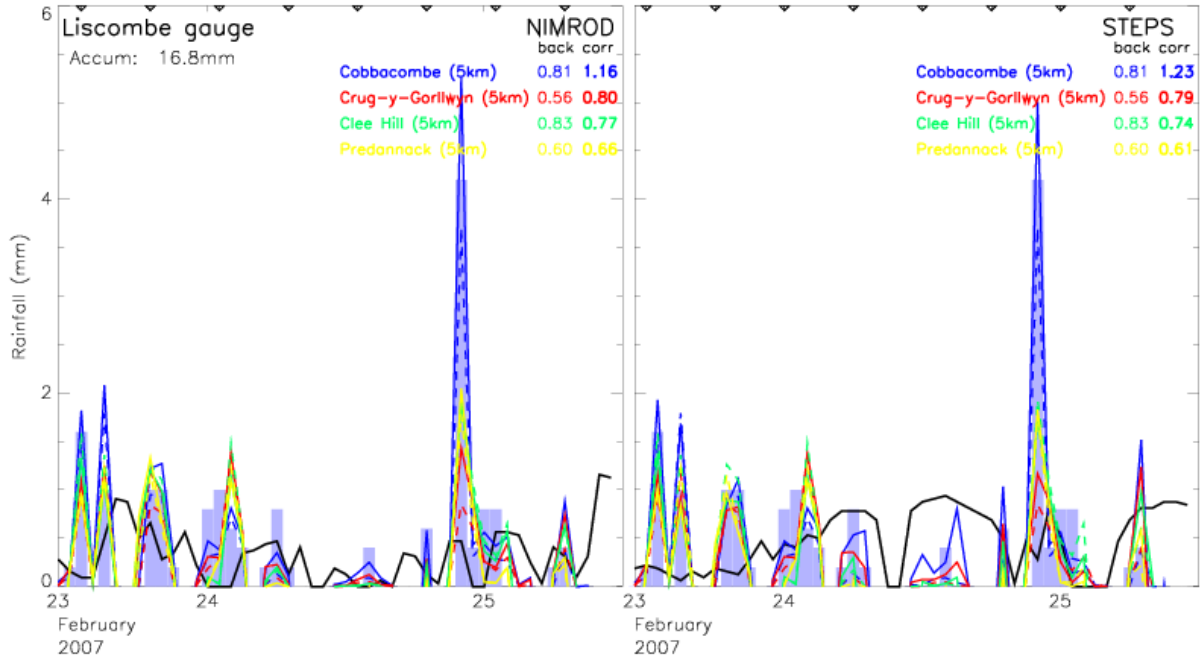


Figure 5.5: Timeseries of rainfall measurements at Liscombe between 1200 UTC on 23 February 2007 and 1200 UTC on 25 February 2007. All other details are as in Figure 5.3.

5.2 Upper Taff

Figure 5.6 compares the hourly rainfall accumulations measured by gauges in the Upper Taff region with the corresponding radar estimates derived using the NIMROD and STEPS orographic corrections. As observed in the Upper Exe region, the rainfall on 22 February 2007 was characterised by two maxima at 0000 UTC and 1100 UTC associated with the passage of the warm and cold fronts shown in Figure 5.1. Gauge measurements at Llyn Y Fan show evidence of considerable orographic enhancement, with a total accumulation almost 3 times larger than measured at Sennybridge. The background radar rainfall estimates are comparable with the gauge measurements at Sennybridge during these periods but are about 75% smaller than the gauge measurements at Llyn Y Fan. This situation leads to an overall under-estimation of the rainfall at Llyn Y Fan while the corrected radar accumulations at Sennybridge are about 70% larger than gauge values. The overestimate is attributed to both NIMROD and STEPS schemes incorrectly applying an orographic correction to background radar data before 0500 UTC on 22 February.

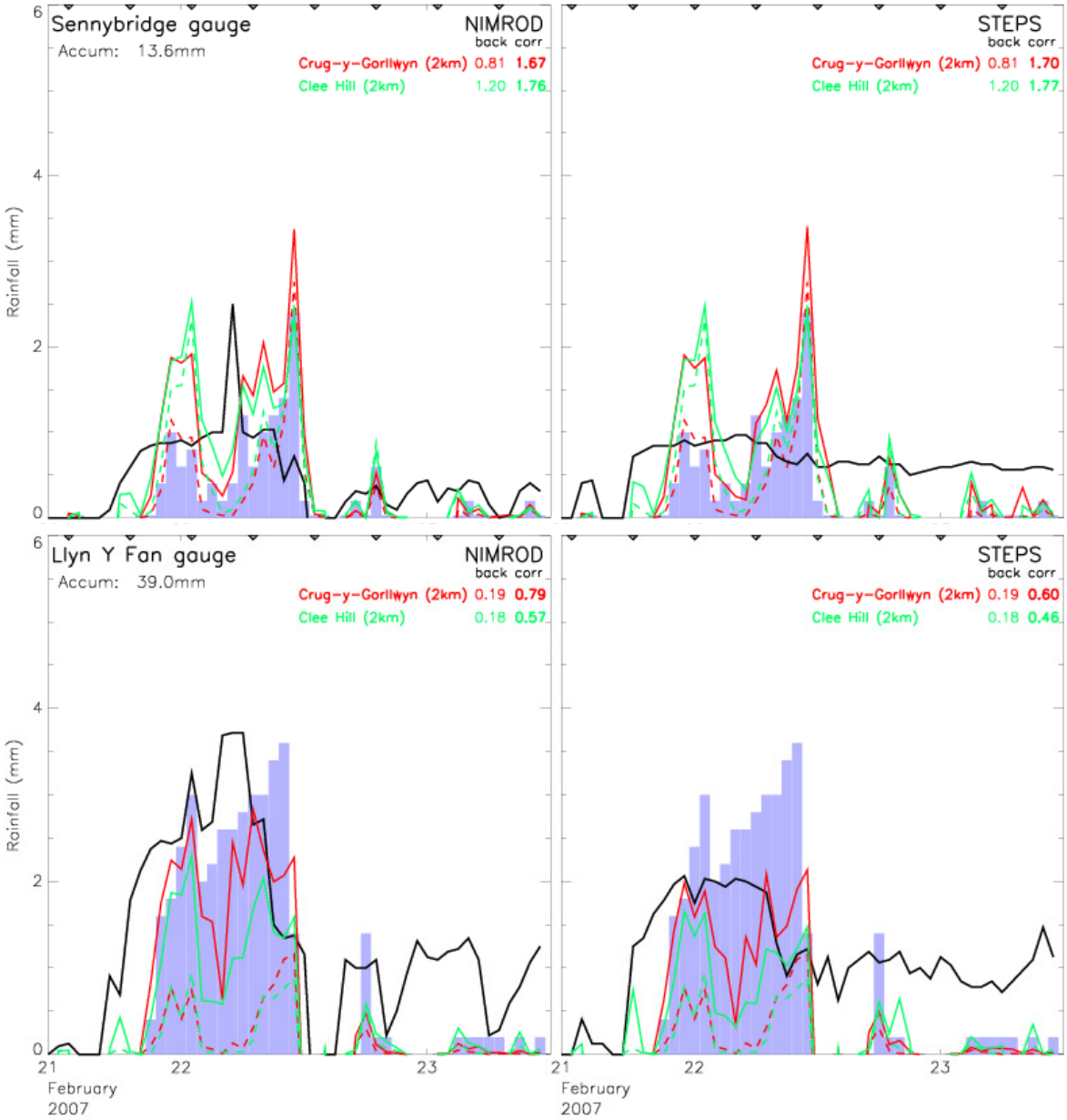


Figure 5.6: Timeseries of rainfall measurements at Sennybridge and Llyn Y Fan in the Upper Taff region between 1200 UTC on 21 and 23 February 2007. All other details are as in Figure 5.3.

Figure 5.7 illustrates the orographic enhancements computed using the NIMROD and STEPS implementations for 0600 UTC on 22 February 2007. These are typical of the enhancement fields applied between 0200 UTC and 0600 UTC when background radar rainfall estimates were very small, suggesting considerable enhancement and rainfall restricted to low levels. As observed across the Upper Exe, the STEPS approach produces considerably more varied enhancements across the region than achieved using a method based on climatology. At Sennybridge, the orographic enhancements calculated by the NIMROD and STEPS were generally of similar magnitude throughout the period of rainfall, resulting in similar corrected radar-derived values in Figure 5.6. There are considerable differences in Figure 5.7 between the enhancement fields produced over the west-east oriented Brecon Beacons range further south. At Llyn Y Fan on the north-western edge of this range, the NIMROD enhancement at 0600 UTC of 3.7 mmh^{-1} is almost twice as large as the STEPS enhancement of 1.9 mmh^{-1}. Comparison of the gauge and radar timeseries at Llyn Y Fan in Figure 5.6 shows that neither correction is sufficient to fully correct the low background rainfall values, but that the larger enhancements predicted by NIMROD leads to better overall agreement of the corrected radar data with gauge accumulations. Table 5.2 summarises the gauge and radar data measured at this time.

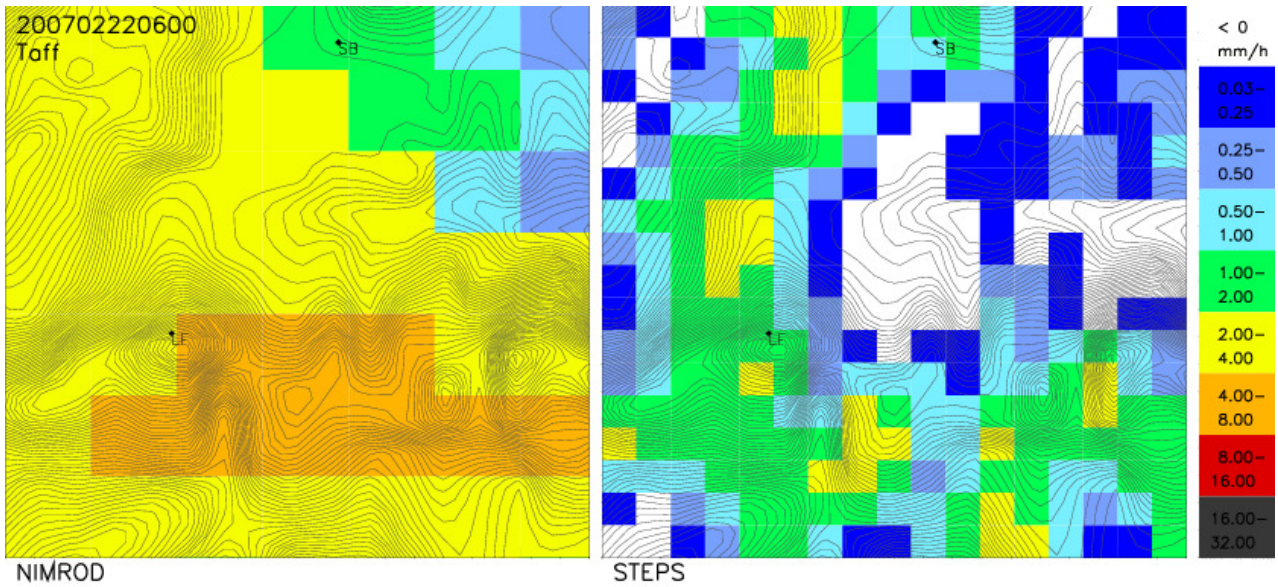


Figure 5.7: Orographic correction fields computed using NIMROD and STEPS methods to be applied to radar data across the Upper Taff region at 0600 UTC on 22 February 2007. The location of the Sennybridge and Llyn Y Fan rain gauges are marked and labelled SB and LF respectively.

Gauge		Radar	Back	NIMROD		STEPS	
				Orog	Corr	Orog	Corr
Sennybridge	1.20 mm	Crug-y-Gorllwyn (2km)	0.20	1.00	1.66	0.88	1.11
		Crug-y-Gorllwyn (5km)	0.12		1.70		1.03
		Clee Hill (2 km)	0.27		1.54		0.89
		Clee Hill (5 km)	0.17		1.76		0.81
Llyn Y Fan	2.80 mm	Crug-y-Gorllwyn (2km)	0.07	3.72	1.96	1.94	1.04
		Crug-y-Gorllwyn (5km)	0.09		2.31		1.26
		Clee Hill (2 km)	0.03		1.12		0.59
		Clee Hill (5 km)	0.03		1.60		0.65

Table 5.2: Comparison between background and corrected radar hourly accumulations (in mm) between 0600 and 0700 UTC on 22 February 2007 and gauge measured hourly accumulations at Sennybridge and Llyn Fan.

Rainfall measurements in the Upper Taff region during the second part of the event between 23 and 26 February 2007 are plotted in Figure 5.8. The corrected radar data generally underestimate surface rainfall measurements with NIMROD-derived estimates up to 12% and 39% lower than gauge values at Sennybridge and Llyn Y Fan respectively. Smaller orographic enhancements computed by STEPS lead to corrected radar estimates up to 31% and 52% lower than gauge value. Figure 5.8 shows that the main contribution to the under-estimation observed at Llyn Y Fan is that the radar measurements do not adequately capture the occasional periods when particularly high hourly rainfall accumulations were observed. Similar events were observed in the analysis of data archived for the Assessment of Radar Data Quality in Upland Catchments project and are thought to be associated with localised embedded convection within a larger-scale frontal rainfall region. Measurements during one such period at 2300 UTC on 24 February 2007 are listed in Table 5.3. The orographic corrections computed at this time are illustrated in Figure 5.9.

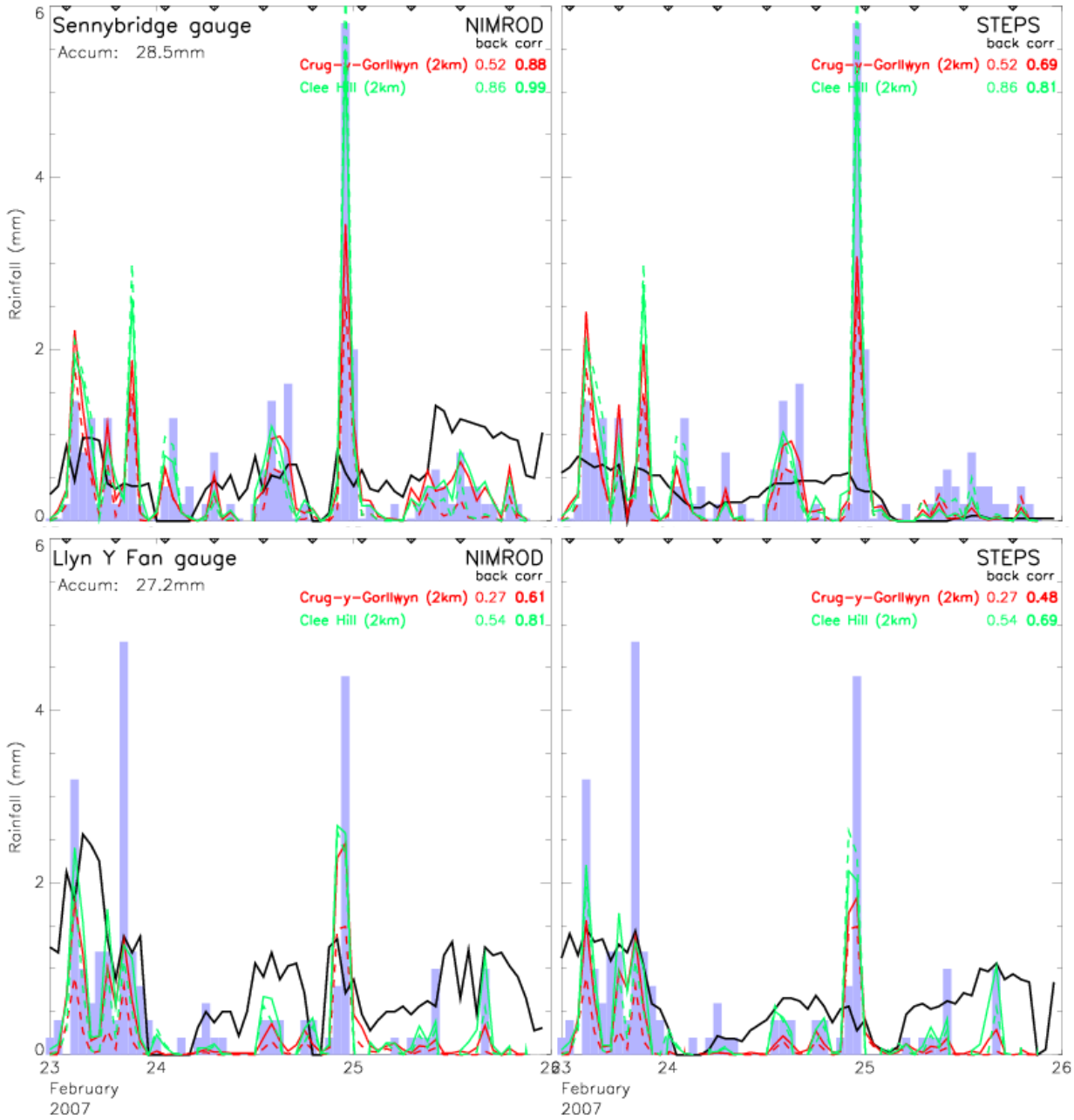


Figure 5.8: Timeseries of rainfall measurements at Sennybridge and Llyn Y Fan in the Upper Taff region between 1200 UTC on 23 and 0000 UTC on 26 February 2007. All other details are as in Figure 5.3.

Gauge		Radar	Back	NIMROD		STEPS	
				Orog	Corr	Orog	Corr
Sennybridge	5.80 mm	Crug-y-Gorllwyn (2km)	2.62	0.56	3.77	0.38	3.36
		Crug-y-Gorllwyn (5km)	2.60		3.85		3.34
		Clee Hill (2 km)	6.33		5.49		5.20
		Clee Hill (5 km)	6.39		5.61		5.25
Llyn Y Fan	4.40 mm	Crug-y-Gorllwyn (2km)	1.49	0.72	2.68	0.29	1.99
		Crug-y-Gorllwyn (5km)	1.86		3.00		2.41
		Clee Hill (2 km)	2.33		2.58		2.03
		Clee Hill (5 km)	2.44		2.54		2.11

Table 5.3: Comparison between background and corrected radar hourly accumulations (in mm) after 2300 UTC on 24 February 2007 and gauge measured hourly accumulations at Sennybridge and Llyn Y Fan.

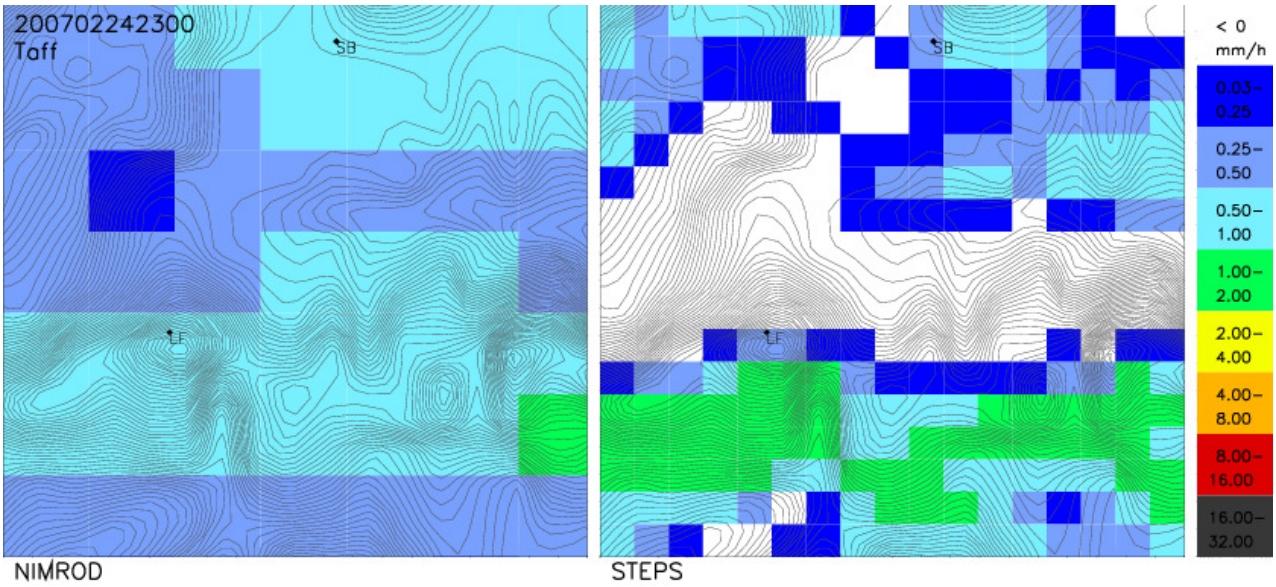


Figure 5.9: Orographic correction fields computed using NIMROD and STEPS methods to be applied to radar data across the Upper Taff region at 2300 UTC on 24 February 2007. The location of the Sennybridge and Llyn Y Fan rain gauges are marked and labelled SB and LF respectively.

5.3 Upper Conwy

Figure 5.10 shows gauge measurements of surface rainfall at Capel Curig during 22 February 2007. The background and corrected rainfall estimates derived from the radars at Clee Hill and Crug-y-Gorllwyn are also plotted along with the current operational (NIMROD) and AS89 (STEPS) orographic corrections. There is a stark difference between the magnitude of the orographic enhancements computed using the NIMROD and STEPS implementations. The maximum correction at Capel Curig computed using the NIMROD climatology of 3.0 mmh^{-1} occurs at 0500 UTC on 22 February 2006 while the STEPS formulation of AS89 predicts a maximum enhancement of only 0.125 mmh^{-1} at 0600 UTC.

As observed from the Assessment of Radar Data Quality in Upland Catchments project analysis, the available radars with coverage across the Upper Conwy region are effective in successfully detecting rainfall. The long range at which the radar measurements are made across the region contribute to background rainfall values considerably under-estimating surface measurements. The

quantitative accuracy of the radar data in this region is therefore critically dependent on the success of the derived orographic corrections in representing reality. Figure 5.10 clearly illustrates that the magnitude of the STEPS correction applied to radar data at Capel Curig is entirely unrepresentative of the strong orographic enhancement observed in reality. Even though the operational NIMROD-derived corrected radar data under-estimate the total gauge accumulation during the event by up to 31%, this provides substantially better agreement than if using the corrections predicted by the STEPS implementation of AS89. The orographic correction fields computed using the NIMROD and STEPS approaches across the Upper Conwy region at 0600 UTC on 22 February 2007 are illustrated in Figure 5.11. These are representative of the correction fields applied during the period of rainfall on 22 February 2007.

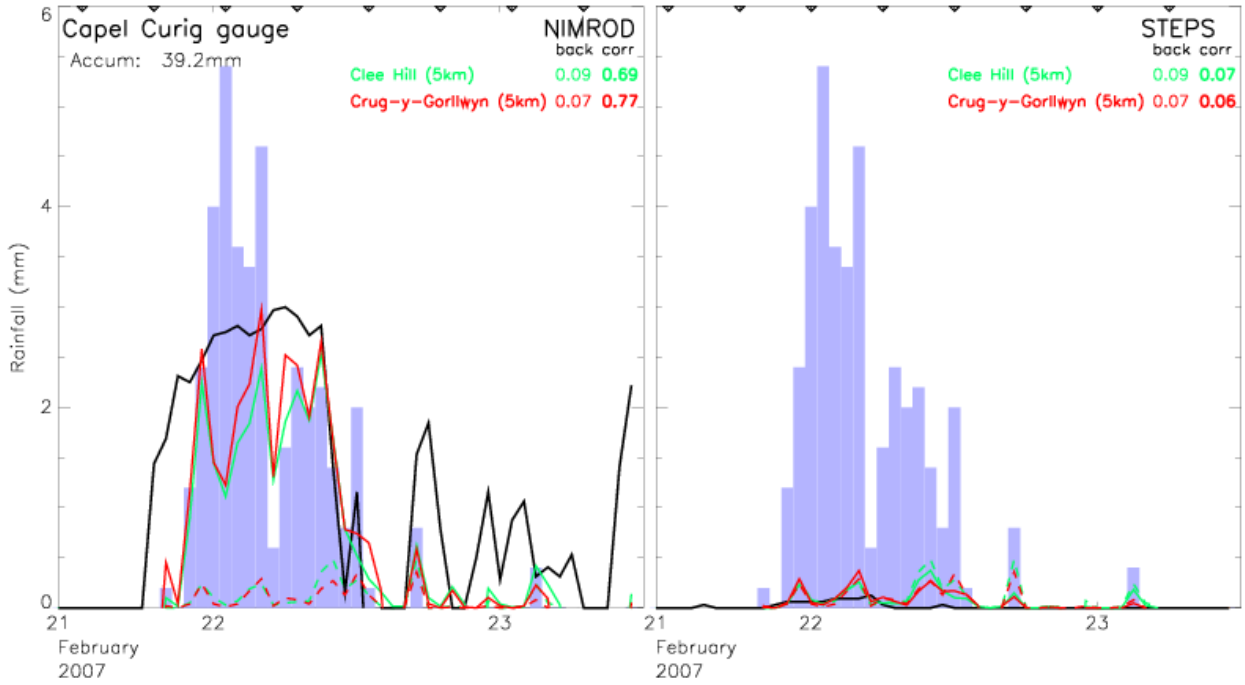


Figure 5.10: Timeseries of rainfall measurements at Capel Curig in the Upper Conwy region between 1200 UTC on 21 and 23 February 2007. All other details are as in Figure 5.3.

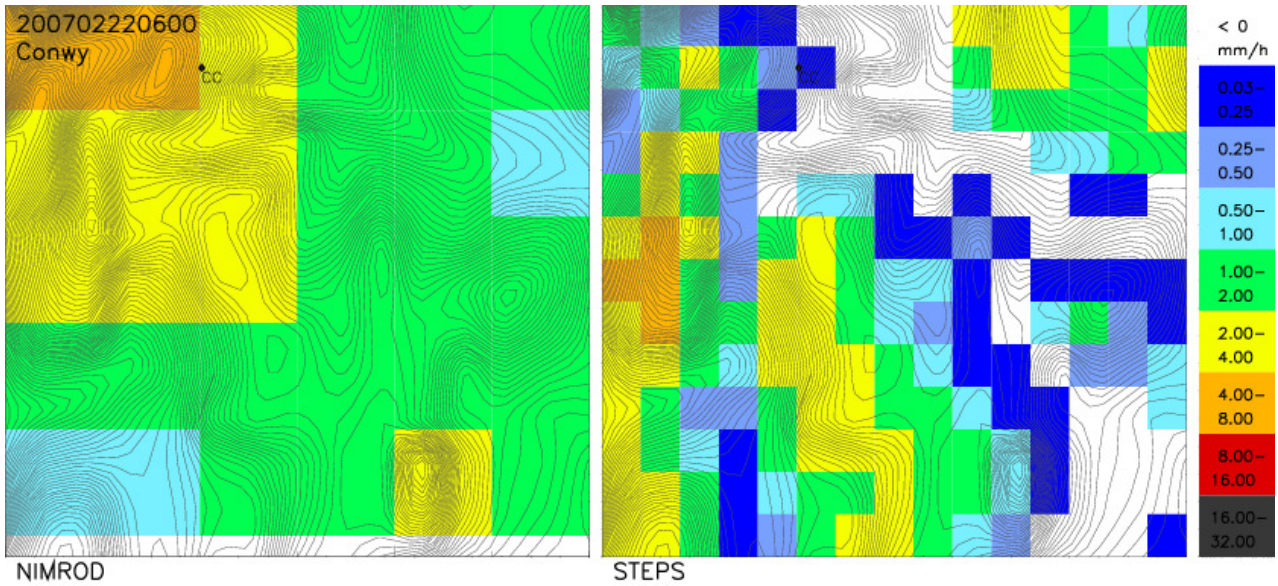


Figure 5.11: Orographic correction fields computed using NIMROD and STEPS methods to be applied to radar data across the Upper Conwy region at 0600 UTC on 22 February 2007. The location of the Capel Curig rain gauge is marked and labelled CC.

Figure 5.11 shows that the small corrections applied at Capel Curig using the STEPS approach result from the increased level of detail introduced by using the AS89 model. In fact, the maximum enhancement in the STEPS correction field in Figure 5.11 of 4.97 mmh^{-1} occurring on the windward slope of Snowdon is larger than the maximum NIMROD enhancement of 4.44 mmh^{-1} to the north of the region. According to the STEPS implementation of AS89, Capel Curig is located in a rain shadow region to the east of the highest parts of the region. At times during the event, Capel Curig is located in a region where no orographic enhancement is predicted by STEPS. Figure 5.10 demonstrates that this is clearly not supported by the measurements of intensive rainfall by the Capel Curig gauge. These data show that the STEPS implementation of the AS89 model produces considerable error in radar-derived surface rainfall rates within valley locations downwind of mountain ranges. The correlation between radar and gauge data plotted in Figure 4.3 show that this case is representative of measurements at Capel Curig for all rainfall over the study period. Substantial improvements to the way in which the model is implemented or to the basis of the physical model itself is therefore required before operational implementation of this approach can be recommended. Improvements to the performance of the orographic correction scheme applied to radar data over upland areas would clearly also lead to improvements in the performance of the STEPS nowcasting system. This issue is discussed in greater detail in Section 6.

The gauge and radar rainfall measurements at Capel Curig during the rest of the event are plotted in Figure 5.12. The NIMROD orographic corrections actually led to a slight over-estimation of surface rainfall by the radars during 23 February 2007 while the incorrect diagnosis of a rain shadow region in the vicinity of Capel Curig leads to a significant under-estimate by about 80% of surface rainfall using the STEPS approach. The overall agreement between the gauge measurements and radar data corrected using the STEPS enhancements is improved by application of more significant orographic corrections during 25 February 2007. This results from a change of wind direction to a more north-westerly direction. Figure 5.13 illustrates the NIMROD and STEPS correction fields during this period. Despite the improved prediction of the observed orographic enhancement, the STEPS-corrected radar data from Clee Hill under-estimated gauge accumulations on 25 February by 50% while the operational NIMROD-corrected radar data under-estimated gauge accumulations by 25%.

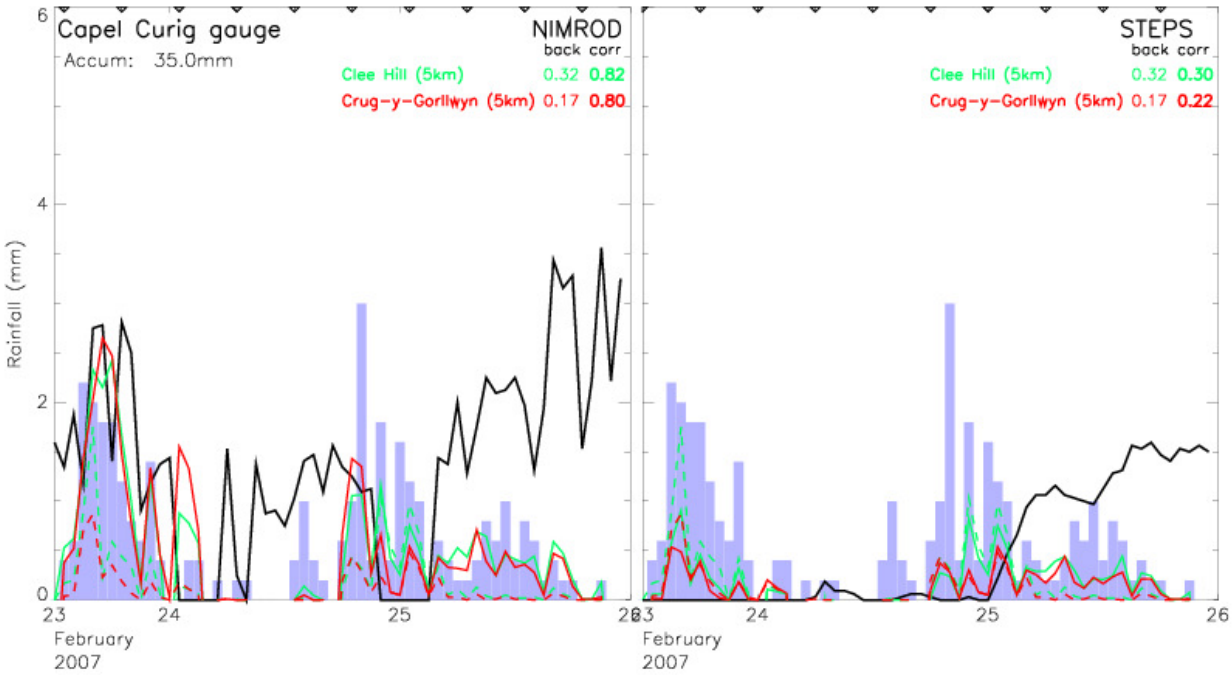


Figure 5.12: Timeseries of rainfall measurements at Capel Curig in the Upper Conwy region between 1200 UTC on 23 February and 0000 UTC on 26 February 2007. All other details are as in Figure 5.3.

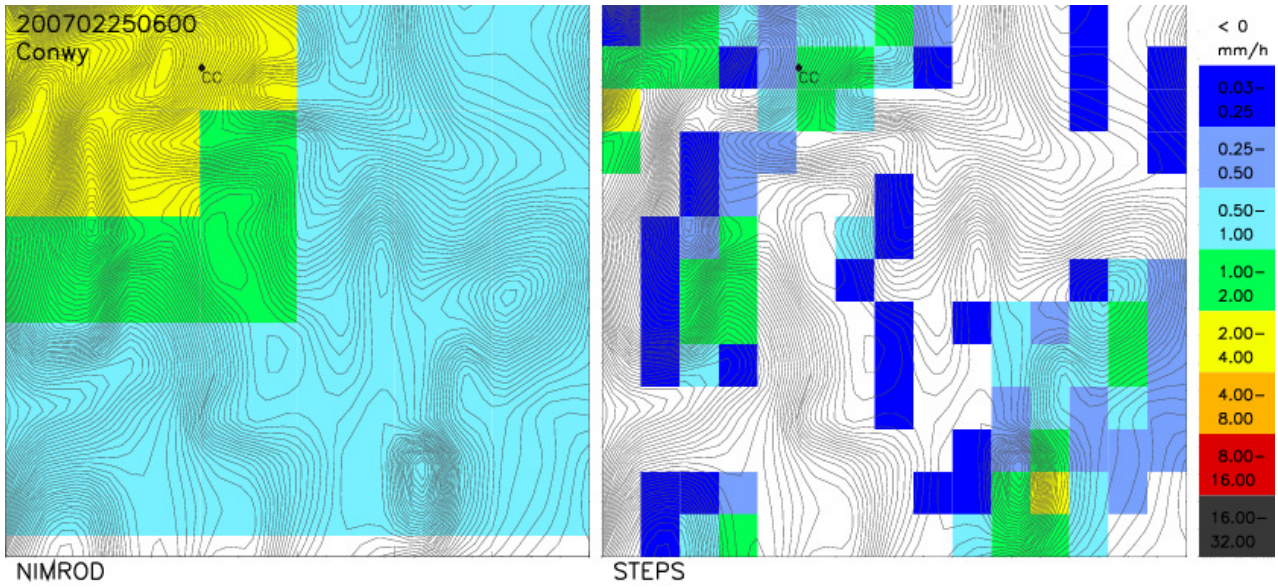
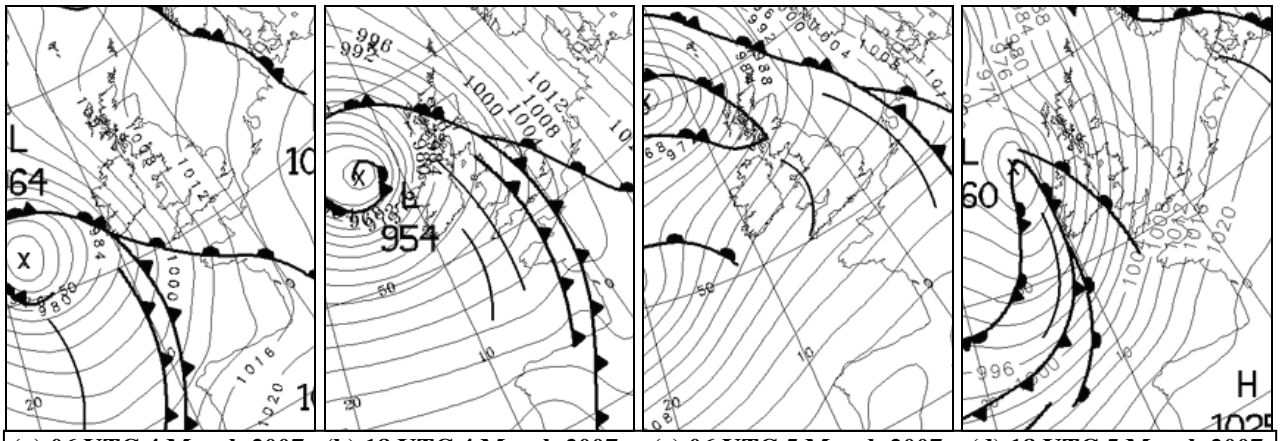


Figure 5.13: Orographic correction fields computed using NIMROD and STEPS methods to be applied to radar data across the Upper Conwy region at 1200 UTC on 25 February 2007. The location of the Capel Curig rain gauge is marked and labelled CC.

4-5 March 2007

The period of prolonged rainfall across England and Wales at the end of February 2007 continued into the first week of March. Figure 6.1 illustrates another series of fronts associated with a rapidly deepening Atlantic depression tracking northwards to the west of the British Isles which resulted in intense orographic rainfall on 4 and 5 March 2007. Strong south-westerly winds were measured during this period. Gusts of up to 30 ms^{-1} were observed in north-western coastal areas during the night of 4 March 2007 for example.



(a) 06 UTC 4 March 2007 (b) 18 UTC 4 March 2007 (c) 06 UTC 5 March 2007 (d) 18 UTC 5 March 2007

Figure 6.1: Surface pressure analysis charts during rainfall period on 4 and 5 March 2007.

6.1 Upper Exe

Figure 6.2 shows timeseries of hourly rainfall accumulations measured over a 48 hour period by the gauges at Liscombe and Brendon Hill in the Upper Exe region. Timeseries of background and corrected radar data at each location are also plotted. There is a break in the archived radar data timeseries after 0000 UTC on 5 March 2007 and no later data are shown.

The results shown in Figure 6.2 show very similar behaviour to the performance of the operational corrections (NIMROD) and the corrections derived from the STEPS implementation of AS89 (STEPS) plotted in Figure 5.3. Example orographic enhancement fields across the Upper Exe region during the period of interest are shown in Figure 6.3. Although the maximum enhancement computed using the STEPS approach of 5.03 mmh^{-1} is more than 4 times larger than the maximum NIMROD-derived enhancement, the operational NIMROD-derived orographic enhancements are generally higher than the corresponding STEPS-derived AS89 values at both gauge locations. Figure 6.2 shows that the NIMROD orographic corrections lead to a 35% overestimation of the total surface rainfall at both gauge locations using data from the closest radar at Cobbacombe Cross. The reduced orographic corrections derived using the STEPS method therefore leads to considerably better overall agreement between corrected radar and gauge measurements. The impact of the NIMROD and STEPS orographic corrections on radar data at longer range is generally similar. At the Liscombe gauge location, the NIMROD corrections lead to a 10-15% overestimation of surface rainfall values while the STEPS corrections lead to an overall underestimation by a similar magnitude. Particular benefit of applying the STEPS corrections is apparent during the night of 5 March 2007 when the operationally corrected radar data over-

estimate surface rainfall by a factor of 2 while the STEPS-corrected radar data are comparable with the gauge measurements. In contrast, the larger corrections applied to radar data at Brendon Hill using the NIMROD scheme leads to a smaller under-estimation of surface rainfall than achieved using the STEPS approach.

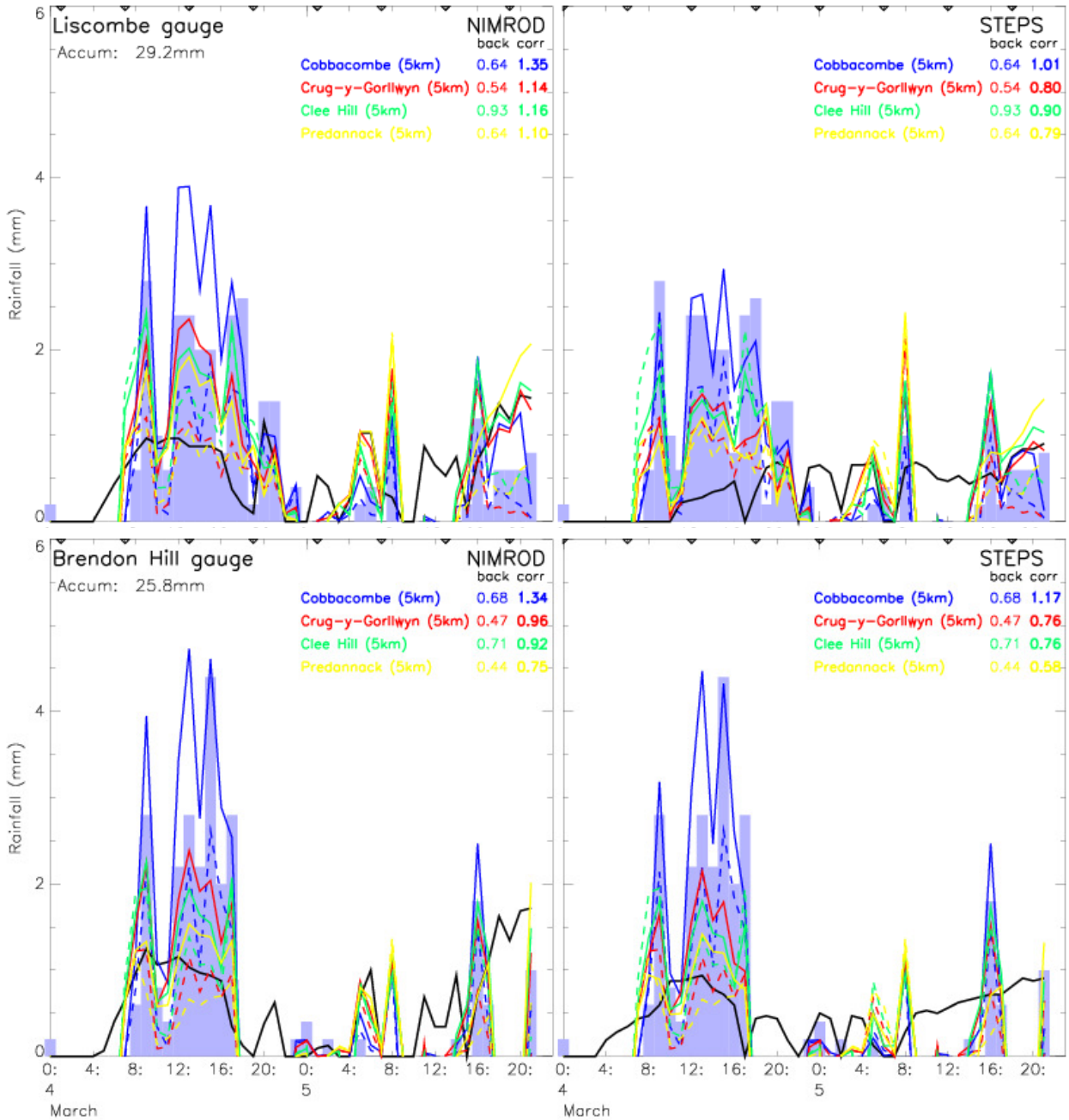


Figure 6.2: Timeseries of hourly rain gauge measurements (bars) and background (---) and corrected (—) radar measurements for the closest pixel to Liscombe and Brendon Hill gauges between 0000 UTC on 4 and 6 March 2007. The total rainfall accumulation for each gauge is listed along with the ratio of total radar to gauge accumulations for each radar (corrected values in bold). Results are shown separately for corrected data using NIMROD and STEPS orographic enhancement fields. The orographic correction is plotted in black.

The AS89 physical model therefore generates realistic orographic enhancements at the available gauge locations in the Upper Exe region, resulting in comparable radar data quality with that currently achieved using the operational correction method based on climatology.

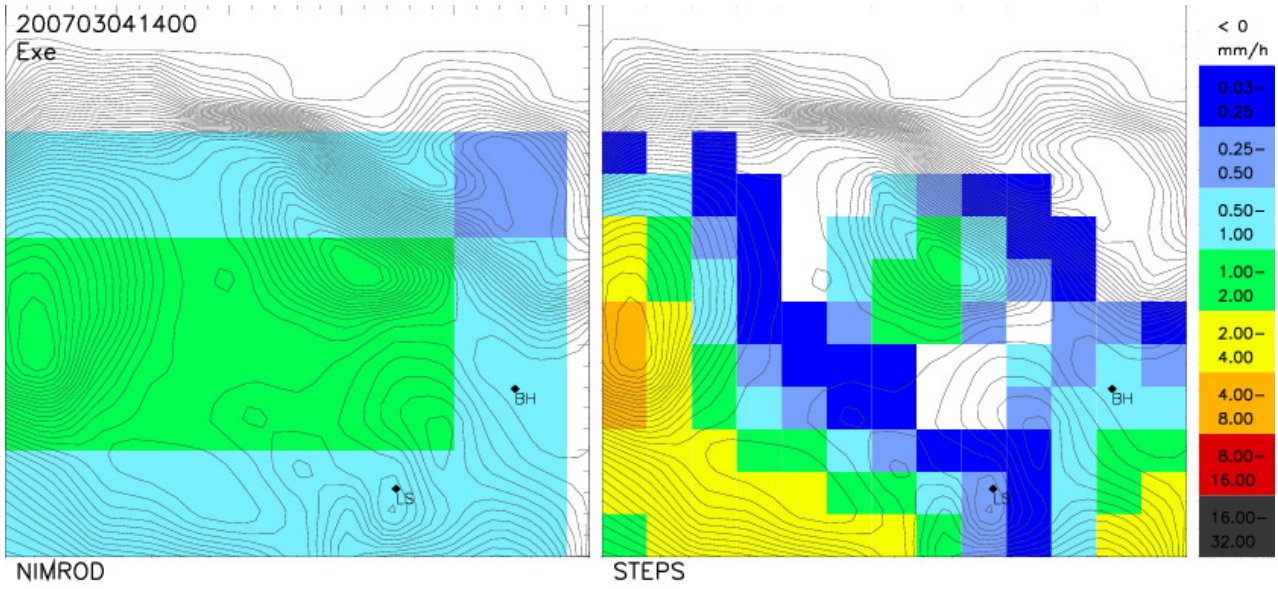


Figure 6.3: Orographic correction fields computed using NIMROD and STEPS methods to be applied to radar data across the Upper Exe region at 1400 UTC on 4 March 2007. The location of the Brendon Hill and Liscombe rain gauges are marked and labelled BH and LS respectively.

6.2 Upper Taff

Figure 6.4 compares the hourly rainfall accumulations measured by the Sennybridge gauge in the Upper Taff region with the corresponding radar estimates using the NIMROD and STEPS orographic corrections. No rain gauge data from Llyn Y Fan was available during this period. The STEPS orographic enhancement timeseries is considerably smoother than the NIMROD-derived values. This is likely to be attributed to the STEPS fields being calculated as a continuous range of values while the NIMROD implementation uses enhancements scaled from fixed correction fields for given wind speed and direction categories.

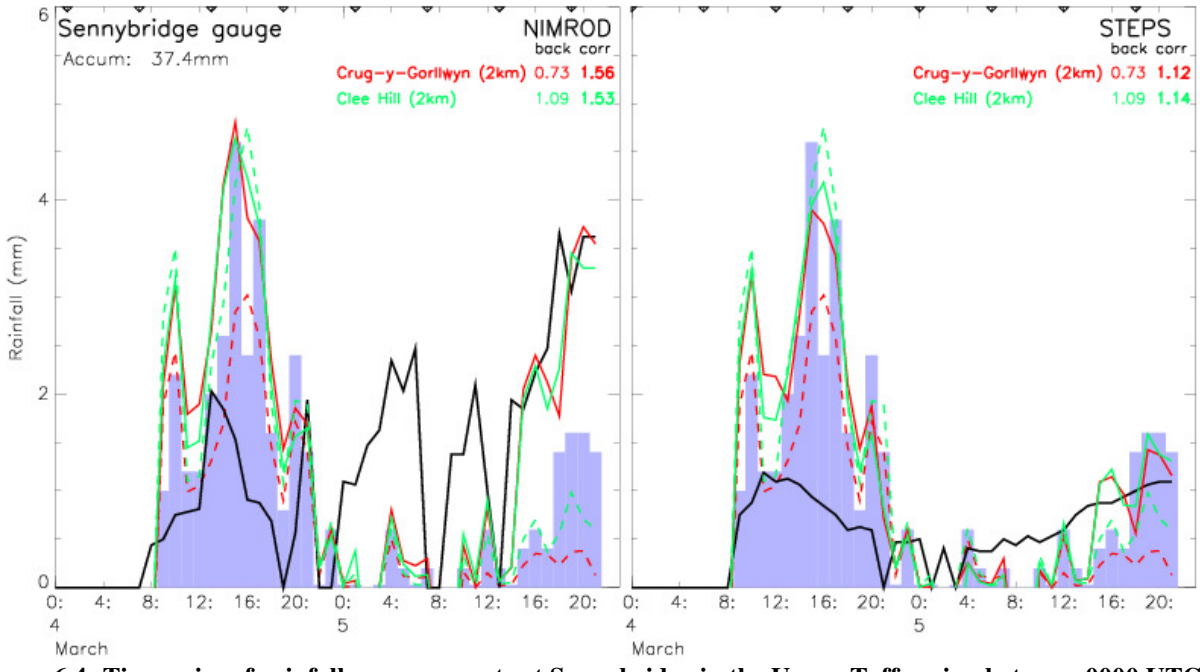


Figure 6.4: Timeseries of rainfall measurements at Sennybridge in the Upper Taff region between 0000 UTC on 4 and 6 March 2007. All other details are as in Figure 6.2.

As observed in the Upper Exe region, Figure 6.4 shows improved agreement between the STEPS-corrected radar data and the gauge measurement due to the application of smaller orographic enhancements than applied using the current operational scheme. A particular failing of the NIMROD scheme in this case is also clear after 1400 UTC on 5 March when orographic enhancements of almost 4 mmh^{-1} are about twice as large as the enhancement observed. The more moderate enhancements of about 1 mmh^{-1} predicted using the STEPS implementation of the AS89 model leads to particularly close agreement between the gauge and radar data. Sample data during this period are listed in Table 6.1. The corresponding orographic enhancement fields are plotted in Figure 6.5.

Gauge		Radar	Back	NIMROD		STEPS	
				Orog	Corr	Orog	Corr
Sennybridge	1.60 mm	Crug-y-Gorllwyn (2km)	0.37	3.06	3.41	1.06	1.42
		Crug-y-Gorllwyn (5km)	0.21		3.47		1.31
		Clee Hill (2 km)	0.98		3.45		1.58
		Clee Hill (5 km)	1.01		3.79		1.61

Table 6.1: Comparison between background and corrected radar hourly accumulations (in mm) between 2000 and 2100 UTC on 5 March 2007 and gauge measured hourly accumulations at Sennybridge.

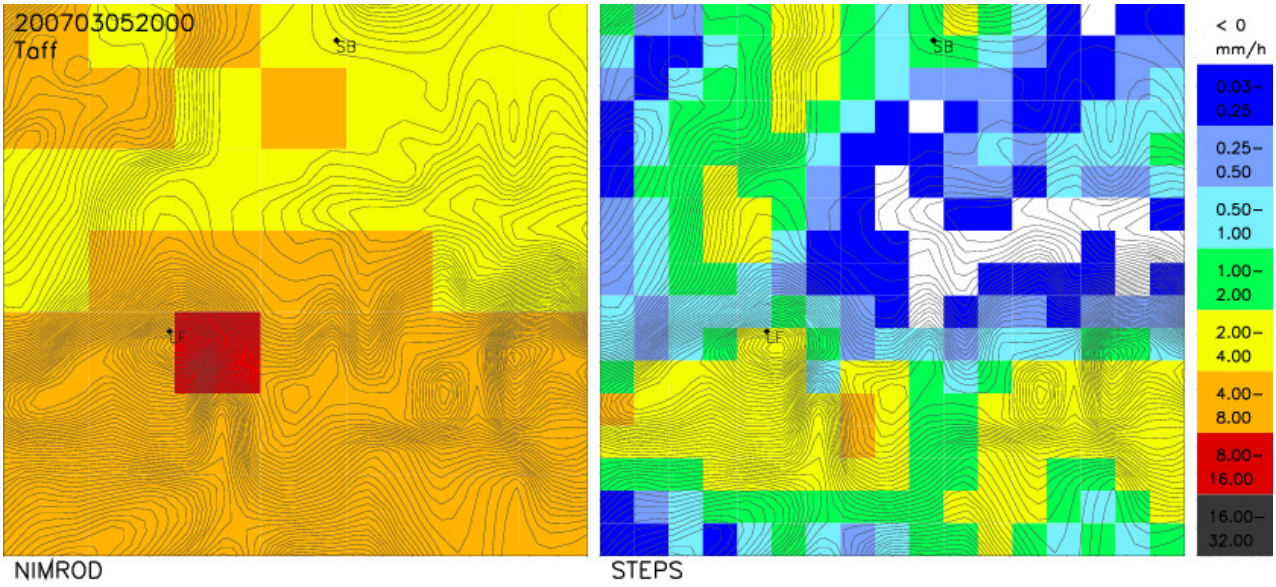


Figure 6.5: Orographic correction fields computed using NIMROD and STEPS methods applied to radar data across the Upper Taff region at 2000 UTC on 5 March 2007. The location of the Sennybridge and Llyn Y Fan rain gauges are marked and labelled SB and LF respectively.

This case provides evidence that the current implementation of the AS89 model used in STEPS can produce improved radar data quality than currently achieved, in at least some locations. The Assessment of Radar Data Quality in Upland Catchments project found data quality in the Upper Taff region to be particularly variable with periods when the orographic corrections led to considerable under and over-estimation of surface rainfall observed. A physical modelling approach may provide particular benefit to radar data quality in such locations where the climatology currently applied as part of the operational processing chain does not consistently represent all cases.

6.3 Upper Conwy

Figure 6.6 shows considerable rainfall accumulations measured at Capel Curig during 4 and 5 March 2007. Comparison of the corrected radar data with gauge measurements shows reasonably poor performance of the NIMROD scheme, even though the overall bias between gauge and radar measurements suggest good agreement. The corrected radar data under-estimate the rainfall observed during 4 March 2007 by about 40% while, as in the Upper Exe and Upper Taff regions, the orographic corrections predicted on 5 March 2007 were a similar magnitude larger than the observed enhancement. Figure 6.6 shows particularly poor performance of the STEPS scheme however due to the application of unrealistically small orographic corrections. Interestingly, the implementation of AS89 in STEPS predicts stronger enhancements after 1500 UTC on 5 March when the NIMROD corrections were found to be too large. The STEPS corrections are insufficient to represent the observed orographic enhancement at this time however. The significant over-estimation of gauge data by NIMROD-corrected radar data and under-estimation by STEPS-corrected radar data is summarised in Table 6.2.

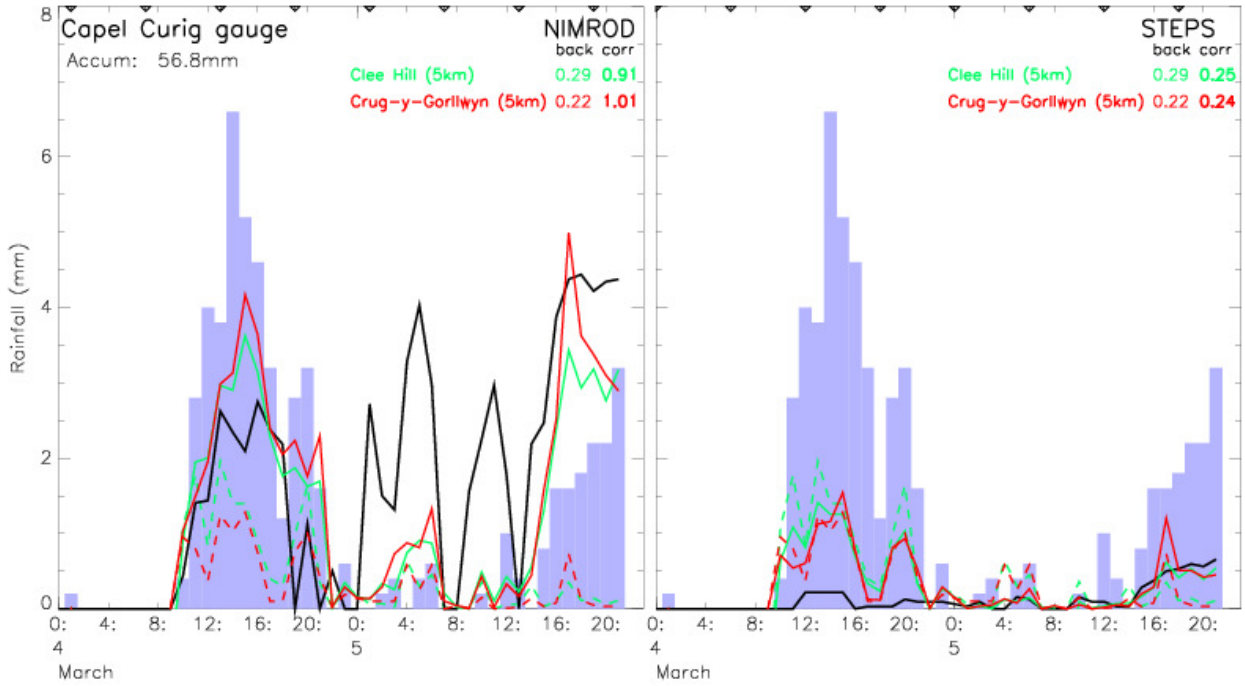


Figure 6.6: Timeseries of rainfall measurements at Capel Curig in the Upper Conwy region on 4 and 5 March 2007. All other details are as in Figure 6.2.

Gauge		Radar	Back	NIMROD		STEPS	
				Orog	Corr	Orog	Corr
Capel Curig	2.20 mm	Clee Hill (5 km)	0.14	4.22	3.18	0.59	0.54
		Crug-y-Gorllwyn (5km)	0.05		3.38		0.51

Table 6.2: Comparison between background and corrected radar hourly accumulations (in mm) between 2000 and 2100 UTC on 5 March 2007 and gauge measured hourly accumulations at Capel Curig.

Figures 6.7 and 6.8 illustrate the orographic correction fields computed across the Upper Conwy region during this event. As identified from the 22 February 2007 case, the STEPS scheme considers Capel Curig to be located in a rain shadow region downwind of the larger terrain to the west of the Upper Conwy region. The rain gauge measurements plotted in Figure 6.6 show this to

be unrepresentative of reality. Developments to the AS89 model implemented to compute orographic enhancements are clearly required before such a scheme can be considered for use in the operational processing of radar data.

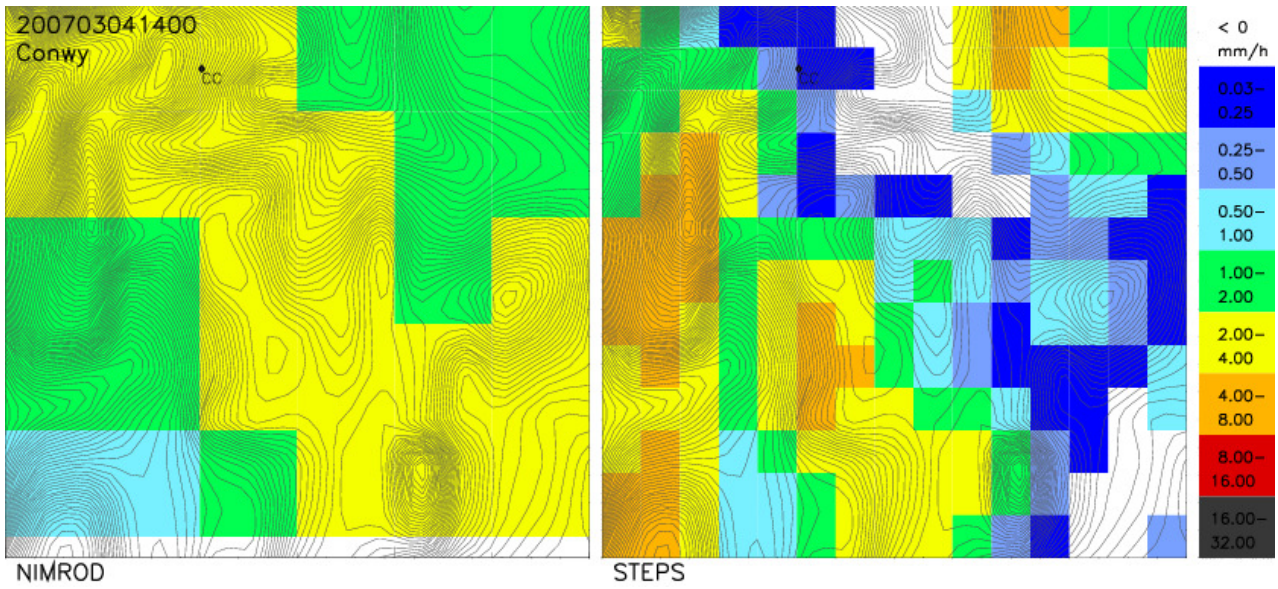


Figure 6.7: Orographic correction fields computed using NIMROD and STEPS applied to radar data across the Upper Conwy region at 1400 UTC on 4 March 2007. The location of the Capel Curig rain gauge is marked and labelled CC.

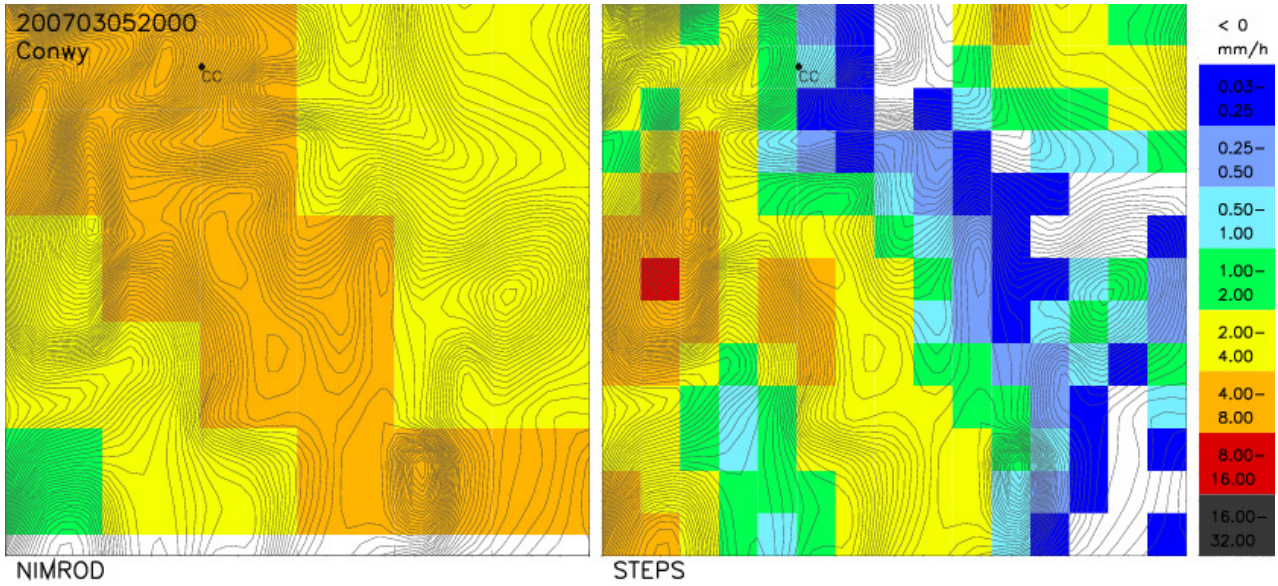


Figure 6.8: Orographic correction fields computed using NIMROD and STEPS applied to radar data across the Upper Conwy region at 2000 UTC on 5 March 2007. The location of the Capel Curig rain gauge is marked and labelled CC.

7 Discussion

The results of the Assessment of Radar Data Quality in Upland Catchments project demonstrated the critical importance of the orographic corrections applied to radar data in upland areas for producing representative surface rainfall values. It was recognised that improvements to the radar data processing was likely to contribute most significantly to improving the quality of radar data for flood forecasting in upland areas. To meet this aim it was envisaged that a more physically-based correction method than currently applied over England and Wales would be required. This development would ensure consistency between the correction fields applied across the radar network in addition to enabling corrections to be defined at higher spatial resolution. Further, the use of a physical model, such as currently applied in STEPS, allows much greater scope to develop the corrections applied in light of scientific and technical progress than currently possible by using the current operational NIMROD method based on climatology. The primary result required from applying a modified orographic correction scheme is an improvement of the quantitative accuracy of radar-derived rainfall data over the current quality quantified as part of the Assessment of Radar Data Quality in Upland Catchments project.

7.1 Summary of radar data quality

This analysis has provided an initial test of the performance of applying a physically-based method for deriving orographic corrections to radar data across England and Wales. The statistical analysis and case-study evidence presented across the Upper Exe and Upper Taff regions has shown comparable agreement between the corrected radar data and available gauge measurements when applying the STEPS physical model enhancements and when applying the current NIMROD enhancement fields. No clear improvement to the data quality is gained by applying the STEPS-derived corrections rather than the NIMROD-derived corrections however. The biggest difference between radar data quality resulting from use of the STEPS implementation of the AS89 model and NIMROD orographic corrections is evident in the Upper Conwy region. This is the region where the magnitude of the corrections applied has been found to have greatest impact on the quantitative accuracy of radar data. While the NIMROD-corrected radar data typically under-estimate the surface rainfall measured by the Capel Curig gauge by about 30%, considerable under-estimation of surface rainfall by over 85% is achieved when applying the STEPS-derived orographic corrections. The case study evidence shows that this is because the gauge is located in a rain shadow region downwind of the mountain ranges in the vicinity of Snowdon during westerly flow periods. While the NIMROD climatology predicts widespread rainfall enhancement over the entire Upper Conwy region in such conditions, the AS89 model implemented in STEPS predicts regions where little or no enhancement occurs. The rain gauge measurements at Capel Curig clearly show that this is not a realistic prediction, which results in considerable errors in the corrected radar data. This study and future verification of developments to the orographic correction scheme would benefit from the availability of surface gauge measurements from a variety of locations in the Upper Conwy region to assess radar data quality in regions where strong enhancements are predicted as well as in the rain shadow regions. The similar performance of the AS89 model enhancements and climatology found in the Upper Exe and Upper Taff regions is partly a result of the available gauges being located in upwind slope locations during the study period which avoids any errors associated with the rain shadow areas predicted by the STEPS implementation of the AS89 model.

7.2 Implications for nowcasting applications

In addition to correcting radar data to account for the orographic enhancement process, the orographic corrections computed by both the NIMROD and STEPS nowcasting systems form a key component of the nowcasting process itself. This is because the precipitation nowcasts rely on extrapolation of the original radar-derived surface rainfall observations and are therefore unable to maintain orographic rainfall over hills and mountains. To overcome this issue, the predicted orographic correction field is subtracted from the initial observation field and then later re-applied to the extrapolated rainfall field over the same geographic locations. At present, the radar data used as input to the STEPS system are corrected using the NIMROD-derived orographic enhancements but the extrapolated rainfall field is then adjusted using the STEPS-derived enhancement. The stark differences between NIMROD and STEPS enhancement identified in this study will therefore impact on the performance of the STEPS system. At locations downwind of hills and mountains, such as Capel Curig, the input radar data will show generally intense rainfall having been corrected with large NIMROD-derived orographic enhancements. For cases when the STEPS system predicts no enhancement in these locations, the intensive rainfall region will be extrapolated downwind rather than only the smaller non-orographic component. This is likely to result in generally diminished rainfall accumulations and potentially large bias errors over upland areas in the STEPS model while the extrapolation of relatively intense rainfall regions may result in generally increased rainfall accumulations downwind of upland areas.

The evidence presented in this study clearly shows that it is unsuitable to apply the orographic enhancements derived from the current implementation of the AS89 model in STEPS to correct the radar data operationally. Further, this study indicates that development of the physical model implemented in STEPS is required to improve the performance of the nowcasting system itself. Work to develop an improved orographic correction scheme to be conducted as part of the Upland Catchments Implementation Project is therefore necessary to address the deficiencies in radar data quality over upland areas identified by the Assessment of Radar Data Quality in Upland Catchments Project. This work should lead to developments of the methods currently used to compute the rainfall enhancement fields in all of the operational nowcasting systems. The improvements to the quantitative accuracy of both the input radar data and resulting short-term precipitation forecasts will have potentially significant benefits for flood-forecasting and warning applications across most regions.

7.3 Options for an improved orographic correction scheme

The Upland Catchment Implementation Project needs to investigate the best approach for computing representative orographic enhancements. The impact of changes to an orographic correction scheme should be measured by comparing the corrected radar data with surface gauges in upland areas as in this study. Consideration of data quality over upland locations across the entire radar network domain may be required to provide the most representative analysis, particularly if the available gauge data is restricted to that archived routinely as part of the Met Office radar processing chain. A modified scheme should only be implemented in the operational systems when improvements to the resultant radar data quality are demonstrated. As at present, it is envisaged that a modified enhancement scheme will be implemented in the operational nowcasting system. A measure of the impact of this change on the performance of the short-range precipitation forecasts is therefore also desirable.

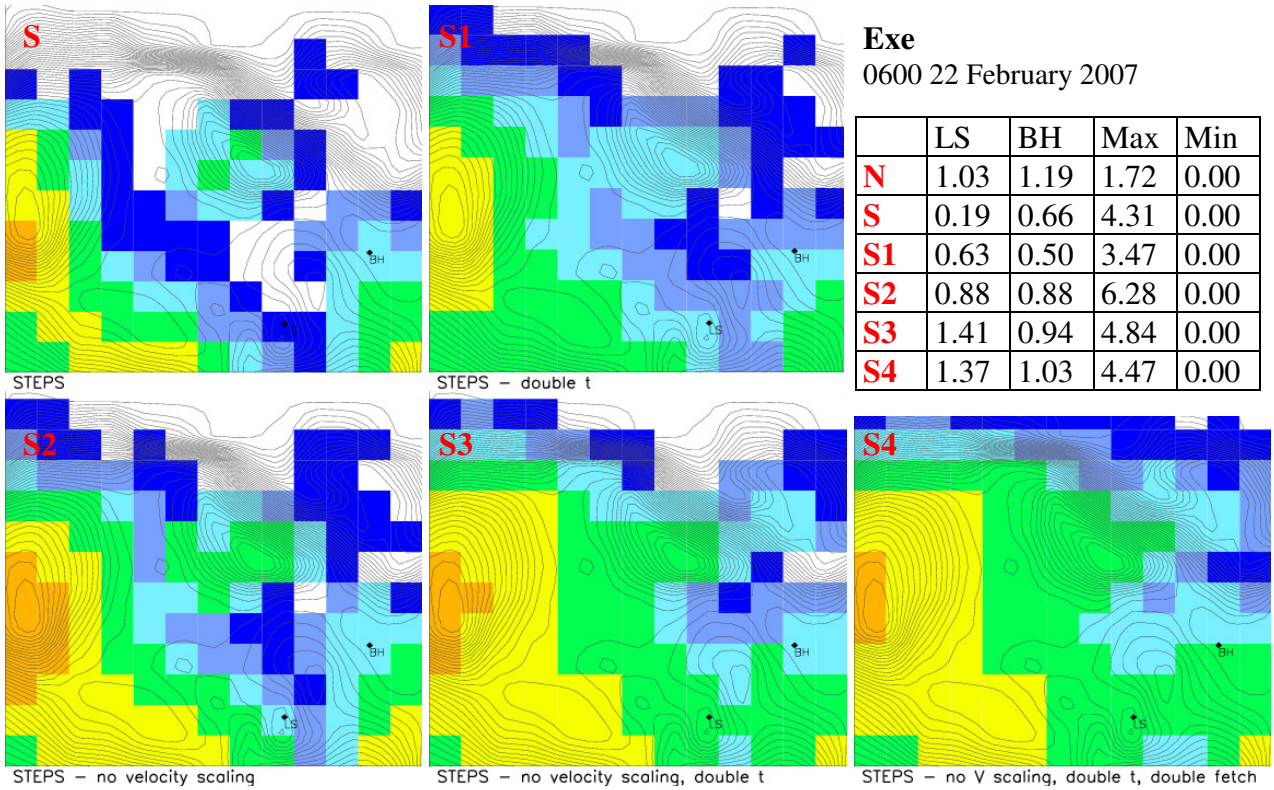
Several options for improving the performance of a physical model approach to computing orographic enhancements might be pursued as part of the Upland Catchment Implementation Project. These options are briefly discussed below.

Modify Alpert and Shafir (1989) model parameters

The AS89 model depends on several tuning parameters, listed in Table 2.1. The current implementation of the model in STEPS follows closely the implementation used to generate the correction fields used over Scotland and continental Europe in the NIMROD system. The primary parameters which impact the magnitude and distribution of orographic enhancements predicted by the AS89 model are

- Efficiency factor f (0.15) – scales the magnitude of local enhancements
- Cloud lifetime t (170 s) – varies weighting applied to upwind enhancements
- Upwind fetch (15 km) – varies distance over which upwind enhancements have influence

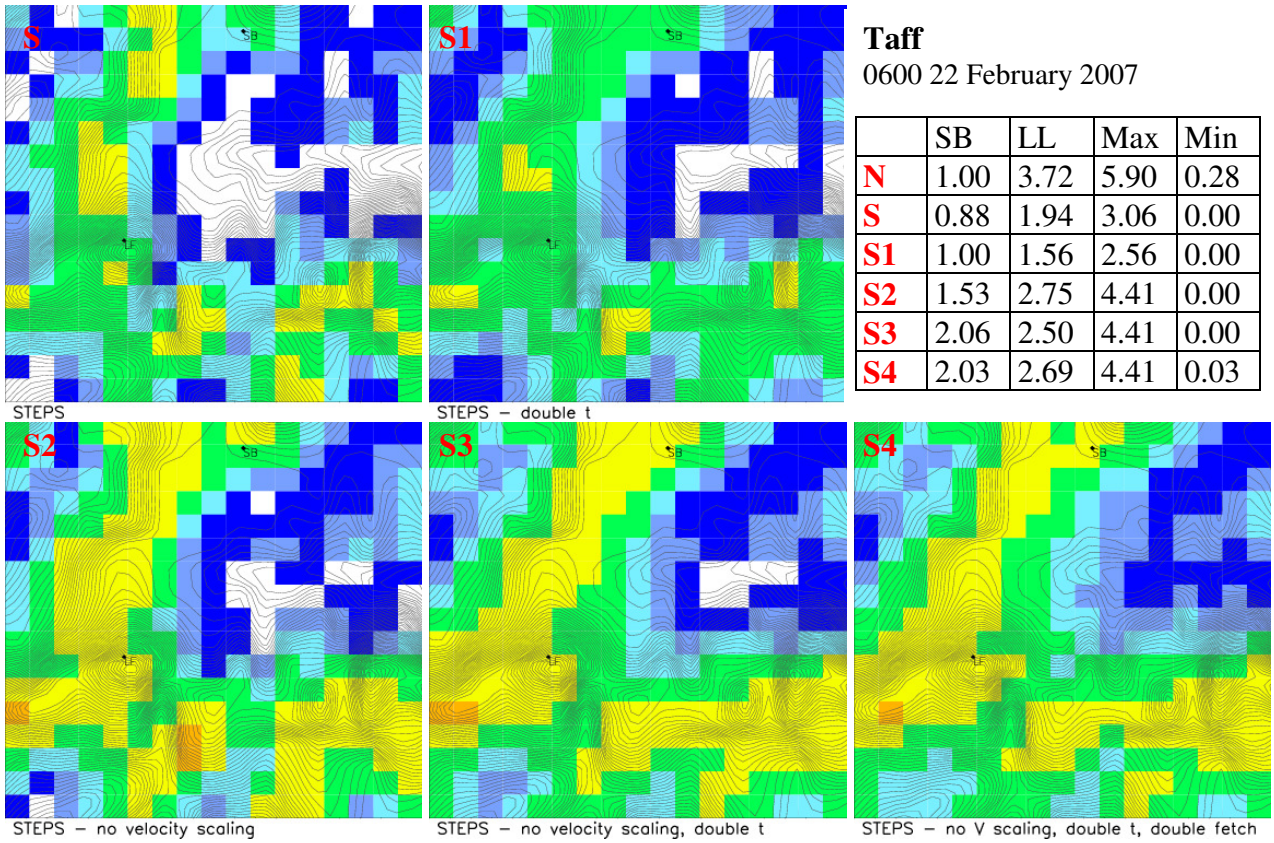
In addition, a multiplier of 0.6 is applied to the wind speed in the STEPS implementation of the AS89 model. This was introduced into the NIMROD version of the scheme to attempt to produce orographic enhancements across Scotland which were generally consistent with the magnitude and distribution of the corrections over England and Wales prescribed by the climatology of Hill (1983). Figures 7.1-7.3 illustrate the impact of the AS89 tuning parameters used in the STEPS system on the orographic enhancements predicted across each upland region at 0600 UTC on 22 February 2007. The corresponding NIMROD fields are plotted in Figures 5.3, 5.6 and 5.10.



Exe
0600 22 February 2007

	LS	BH	Max	Min
N	1.03	1.19	1.72	0.00
S	0.19	0.66	4.31	0.00
S1	0.63	0.50	3.47	0.00
S2	0.88	0.88	6.28	0.00
S3	1.41	0.94	4.84	0.00
S4	1.37	1.03	4.47	0.00

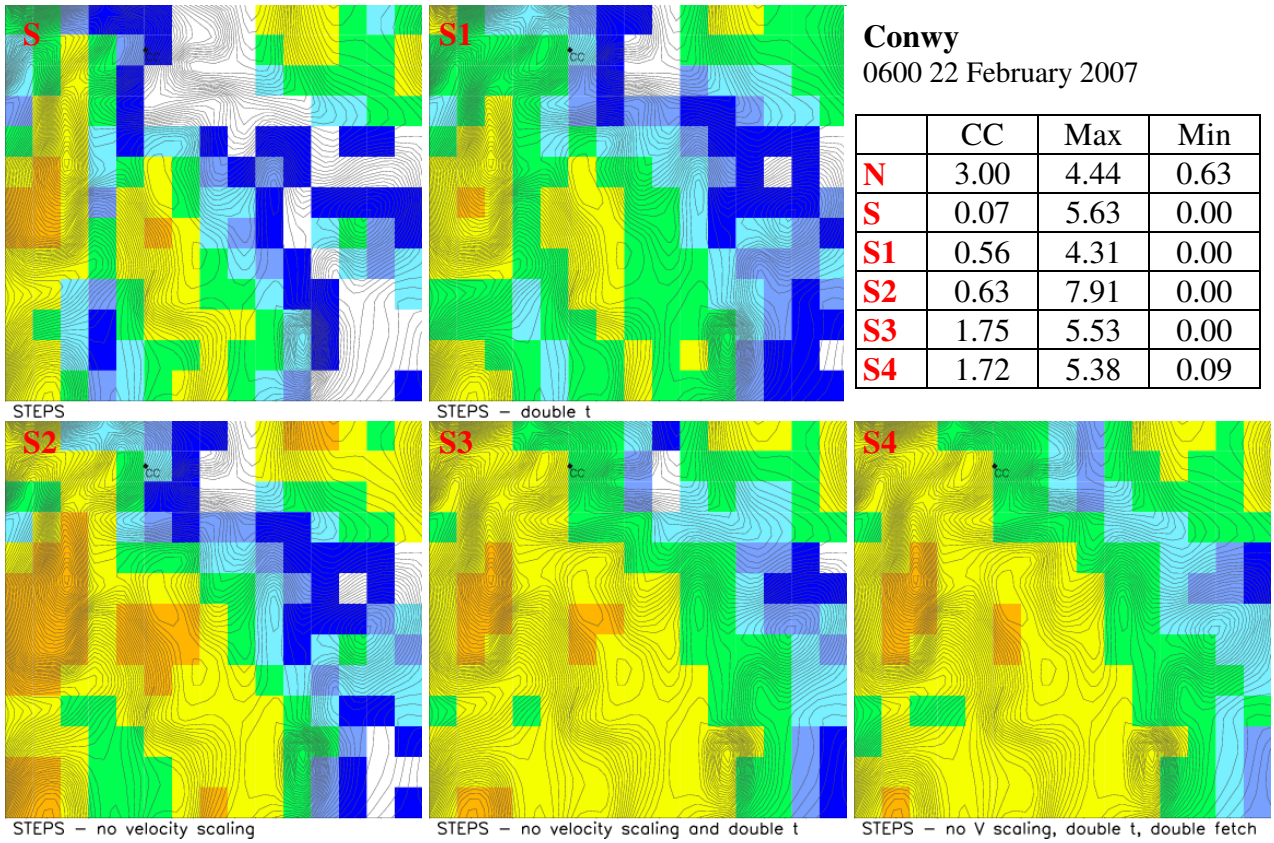
Figure 7.1: Orographic correction fields across the Upper Exe region at 0600 UTC on 22 February 2007 derived using different implementations of the Alpert and Shafir (1989) model. The table lists corrections calculated for the pixels closest to the gauges at Liscombe (LS) and Brendon Hill (BH) and the maximum and minimum values within the region shown. Values are quoted for enhancements computed using the NIMROD climatology (N) and each variation of the STEPS model (S) shown.
S: current STEPS implementation of Alpert and Shafir (1989) model, S1: as in S with typical lifetime of cloud doubled to t=340 s, S2: as in S with velocity scaling removed, S3: as in S with velocity scaling removed and t=340 s, S4: as in S with velocity scaling removed, t=340 s and maximum upwind range of influence doubled to 30 km.



Taff
0600 22 February 2007

	SB	LL	Max	Min
N	1.00	3.72	5.90	0.28
S	0.88	1.94	3.06	0.00
S1	1.00	1.56	2.56	0.00
S2	1.53	2.75	4.41	0.00
S3	2.06	2.50	4.41	0.00
S4	2.03	2.69	4.41	0.03

Figure 7.2: Orographic corrections across the Upper Taff region using different implementations of the Alpert and Shafir (1989) model. The table lists corrections for pixels at Sennybridge (SB) and Llyn Y Fan (LL) gauges.



Conwy
0600 22 February 2007

	CC	Max	Min
N	3.00	4.44	0.63
S	0.07	5.63	0.00
S1	0.56	4.31	0.00
S2	0.63	7.91	0.00
S3	1.75	5.53	0.00
S4	1.72	5.38	0.09

Figure 7.3: Orographic corrections across the Upper Conwy region using different implementations of the Alpert and Shafir (1989) model. The table lists corrections for pixels at Capel Curig (CC).

The results shown in Figures 7.1-7.3 illustrate that the orographic enhancements predicted by the AS89 model can be altered considerably by varying the tuning parameters used. The influence of both local and upwind enhancements in determining the orographic correction applied at each grid point leads to both positive and negative changes in the magnitude of the correction at each gauge site considered in addition to variations in the larger-scale distributions. The largest changes to the magnitude of the corrections results from removing the scaling applied to velocity data. The relevance of this scaling applied to model data produced by the UK 4km model is unclear and a more robust assessment of the validity of the velocity scaling in the STEPS implementation in required.

The case study analyses presented in Sections 5 and 6 show that the biggest difference between the orographic enhancements produced by the current NIMROD and STEPS implementations is that the STEPS scheme predicts significant rain shadow regions downwind of hills and mountains while the NIMROD scheme predicts widespread enhancements across upland regions. This was found to result in particularly poor radar data quality when comparing with gauge measurements at Capel Curig in the Upper Conwy region (Figure 5.10). Figures 7.1-7.3 show that it is possible to generate enhancements across broader regions using the AS89 model by removing the velocity scaling and increasing the cloud lifetime and upwind fetch parameters. The increased influence of the upwind terrain on enhancements at Capel Curig illustrated in Figure 7.3 for example leads to a 25-fold increase of the orographic correction predicted by the current STEPS implementation from 0.07 mmh^{-1} to a value of 1.75 mmh^{-1}.

Given their influence on the orographic enhancements predicted by the AS89 model, a systematic assessment of the impact of each tuning parameter on the quality of radar data over upland areas is necessary. This would require computing corrections using different implementations of the AS89 model over a period of several weeks to assess the best approach to generate representative orographic enhancements and surface rainfall estimates.

Correct for the impact of terrain resolution

Comparison of the magnitude and distribution of orographic corrections produced by the NIMROD and STEPS nowcasting systems across Scotland highlights considerable differences between the predictions of the AS89 model produced by each implementation, despite the use of similar tuning parameters. An example comparison is shown in Figure 2.1. In this particular case, the NIMROD corrections across Scotland are generally higher and more widespread that the STEPS corrections. These differences might be attributed to

- Different input mesoscale model data
- Different resolution of input mesoscale model data
- Different resolution of terrain data

Although an assessment of the relative performance of the 5 km resolution data generated from the North Atlantic European mesoscale model output and 2 km resolution post-processed data generated from the UK 4km model is beyond the scope of this study, justification for the most appropriate model data and resolution to produce representative orographic enhancements is desirable as part of the Upland Catchments Implementation project. Trials to generate orographic enhancements by applying the AS89 method using operational mesoscale model data at horizontal resolutions of 5, 4 and 2 km should illustrate the impact of model data resolution on the distribution of orographic enhancement fields and its effect on radar data quality.

As the STEPS orographic corrections are calculated in real-time, the AS89 model is applied to terrain data with the same 2 km horizontal resolution as the input mesoscale model data. In contrast, the enhancement fields applied in the NIMROD system were computed only once using considerably more detailed terrain data with 500 m horizontal resolution to produce high resolution enhancements before these were up-scaled to coarser resolution. The influence of terrain resolution on the predictions of the AS89 model is illustrated in Figure 7.4. The orographic enhancements predicted by the AS89 model along an idealised terrain transect defined at different horizontal resolutions are plotted. The smooth terrain cases shows corrections over a continuous obstacle defined at each resolution while the rough terrain case shows corrections over the continuous obstacle with a more realistic representation of the small-scale ridges and troughs found in hilly regions.

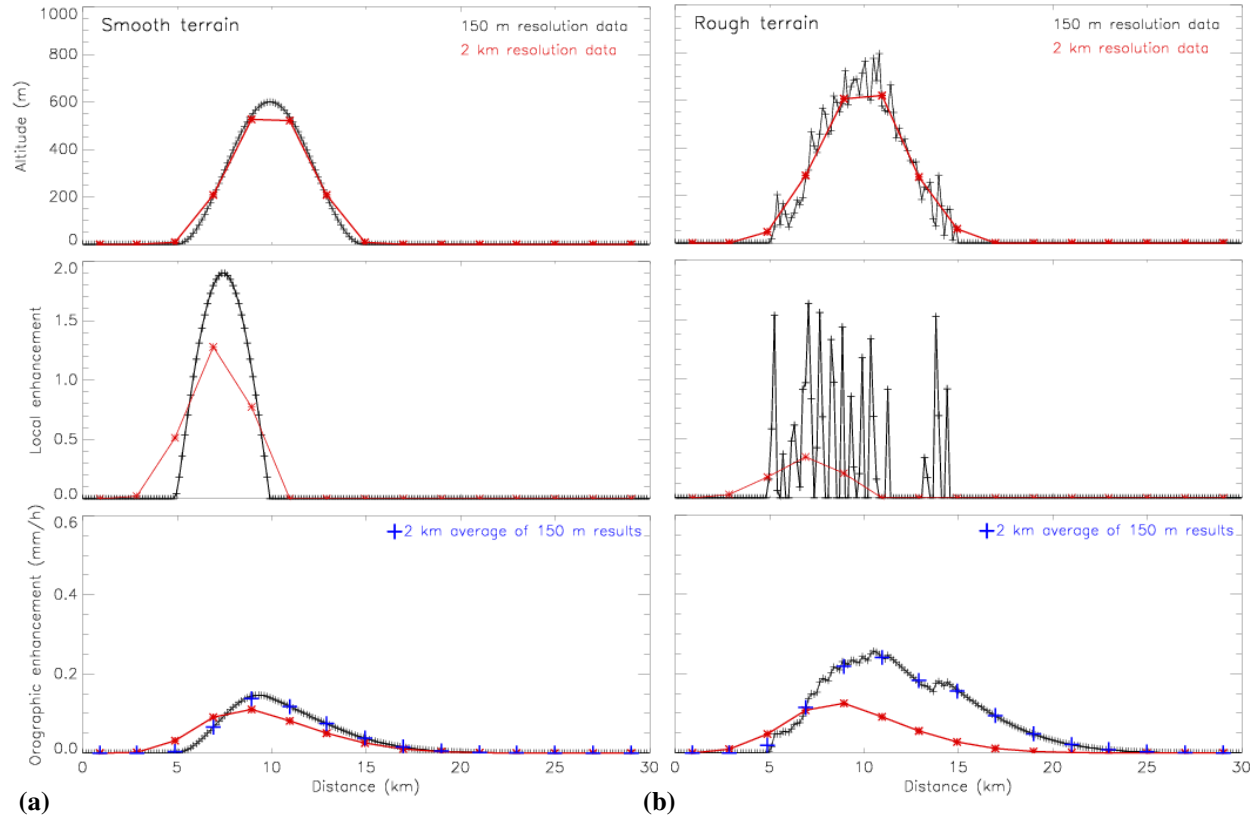


Figure 7.4: Comparison of the orographic enhancement predicted by the Alpert and Shafir (1989) model applied to an idealised mountain ridge defined at 150 m and 2 km horizontal resolution. Enhancements are computed for (a) continuous obstacle shape and (b) more realistic mountain ridge profile. Top: terrain shape at each resolution, Middle: local enhancement field P_0 based on the local slope calculated at each grid point, Bottom: orographic enhancement at each resolution based on weighted average of upstream corrections. The coarser resolution average of corrections computed using high resolution terrain data is also plotted.

Figure 7.4 demonstrates that terrain resolution has a considerable impact on the results of the AS89 model, or any orographic correction scheme which depends on the local terrain slope ∇Z_s. The smooth terrain calculation shows that use of coarse resolution terrain data results in a general underestimation of the local slope across each grid point, particularly near the hill crest. This leads to a 25% reduction between the maximum enhancement predicted for the 150m and 2 km resolution terrain plotted in Figure 7.4(a). Sampling the idealised terrain shape at 1 km resolution leads to only a 10% reduction from the maximum enhancement predicted at 150 m. The position of the maximum enhancement is about 1 km upwind of the hill crest in each case.

The impact of terrain resolution on the orographic enhancement field is more significant if considering more realistic terrain profiles, where the influence of smaller-scale ridges and valleys across an upland area contribute to the enhancement process. Figure 7.4(b) shows an example of this situation. In terms of the AS89 model, each small-scale ridge and valley defined by the high-resolution terrain induces a local enhancement at grid points downwind of the main ridge crest wherever the local slope is positive. In contrast, the coarse resolution results show no local enhancements downwind of the crest and all orographic corrections in such regions result from advection of upwind enhancements. The net result illustrated in Figure 7.4(b) is that the maximum enhancement across the ridge predicted using the 150 m resolution data is about twice as large as that predicted using the 2 km terrain. While the location of maximum enhancement predicted using the 2 km resolution terrain remains about 1 km upwind of the main ridge crest, maximum enhancement for the higher resolution obstacle is located at about 1 km downwind of the crest. The distribution of orographic enhancement plotted in Figure 7.4(b) shows that the correction applied a distance of 5 km downwind of the main ridge crest when using 150 m resolution terrain data is of comparable magnitude to the maximum enhancement predicted using the 2 km terrain data. These results suggest that the magnitude of orographic enhancements calculated using the AS89 model in areas such as Capel Curig, located downwind of Snowdon in westerly winds, are critically dependent on the resolution of the terrain used to compute the correction field.

The results shown in Figure 7.4 are also consistent with the correction fields plotted in Figure 2.1 with the higher resolution terrain used to generate the NIMROD enhancements across Scotland producing broader areas of stronger enhancements than generated using the STEPS implementation based on relatively coarse resolution terrain data. This is supported by the correction fields produced using terrain data sampled at 500 m and 2 km shown in Figure 7.5.

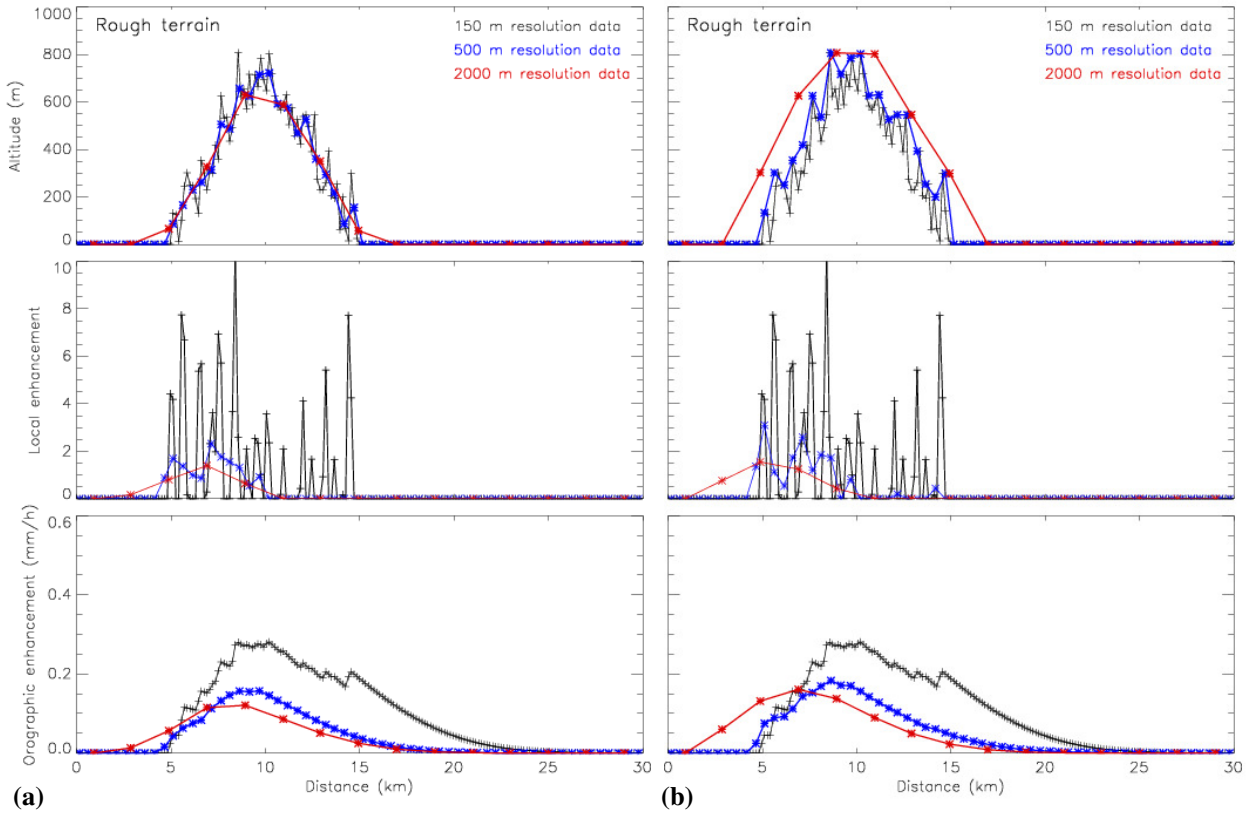


Figure 7.5: As in Figure 7.4 showing enhancements are computed for a realistic mountain ridge profile sampled at 150m, 500m and 2000m horizontal resolution using (a) mean and (b) maximum terrain height in each sample.

Figure 7.5 also shows the sensitivity of the AS89 model to the method by which the terrain data is sampled. When data is sampled using the maximum terrain height within a horizontal range (Figure 7.5(b)), the resulting maximum orographic enhancements are a factor of 16.5% and 33.2% larger for sampling at 500 m and 2000 m horizontal resolution respectively than when the terrain data is sampled using the mean height within a range. Further differences between the NIMROD and STEPS derived orographic enhancements across Scotland plotted in Figure 2.1 might therefore be attributed to the STEPS AS89 model being applied to a mean terrain height dataset at 2000 m resolution while the NIMROD field was derived using a maximum terrain height dataset at 500 m resolution. Investigation of the impact of this detail on the orographic corrections derived using real terrain data is required.

The orographic corrections predicted by the AS89 model are therefore highly sensitive to the horizontal resolution of the terrain data used to compute the local slope. The particularly poor agreement between the STEPS-corrected radar data and gauge measurements at Capel Curig suggests that the 2 km resolution terrain data currently used to generate orographic enhancements in STEPS is of insufficient resolution to produce realistic enhancements downwind of hills and mountains. It is envisaged that the use of higher-resolution terrain data would lead to generally larger orographic corrections across broader geographical areas as in the current NIMROD scheme. Further study is required to investigate the most appropriate resolution terrain data required to compute realistic orographic enhancements. There is clearly a physical limit to the scale over which changes in the surface slope influence the larger-scale convergence and divergence of moisture as air flows over upland areas and a limit to the scale over which it is appropriate to compute the local slope. A systematic study of the influence of terrain data resolution on the distribution of orographic corrections is required and of its impact on the resulting radar data quality.

This work, to be conducted as part of the Upland Catchments Implementation project, must also meet the challenge of developing a method by which orographic enhancements can be computed at the most appropriate horizontal resolution while the correction scheme can still be operated in an on-line operational manner. Should it prove impractical to compute corrections in real-time using higher-resolution data, it may be necessary to develop some scaling algorithms to account for the influence of sub-grid scale variations of the terrain slope on orographic corrections computed at a coarser horizontal resolution.

Investigate alternative approaches to compute corrections

The results discussed in this study have shown evidence for comparable radar data quality in the Upper Exe and Upper Taff regions using orographic enhancements computed using the NIMROD climatology and STEPS physical model approaches. This suggests that the use of an improved implementation of the AS89 model can bring benefits in improving radar data quality in upland areas beyond that quantified by the Assessment of Radar Data Quality in Upland Catchments project. It is envisaged that these benefits will be realised as a result of the investigations and developments proposed as part of the Upland Catchments Implementation project.

A range of other physical models have been previously developed to predict the orographic enhancement induced by hills and mountains. Should developments to the implementation of the AS89 model prove unsuccessful in improving radar data quality over upland areas, it may be necessary to consider the merits of using alternative model formulations (e.g. Bader and Roach

1977, Carruthers and Choularton 1983, Robichaud and Austin 1988, Weston and Roy 1994, Sinclair 1994). The models developed by Bader and Roach (1977), Carruthers and Choularton (1983) and Robichaud and Austin (1988) are two-dimensional models involving more complex representation of microphysical processes than included in the AS89 model. The performance of these models in an operational environment is not known. Similarly to the AS89 model, the performance of the simpler models developed by Sinclair (1994) and Weston and Roy (1994) will depend on determining the most appropriate tuning parameters and be prone to errors resulting from estimating the topographic ascent $V.\nabla Z_s$ at an inappropriate horizontal resolution.

Investigation of using additional model parameters or data to adapt the operation of the AS89 approach may prove to be more beneficial. For example, consideration of the vertical wind speed predicted by the mesoscale model may provide a more representative measure of the large-scale convergence as air passes over hills and mountains than achieved using the local slope parameterisation used in the AS89 model. Alternatively, diagnosis of stratiform or convective cloud conditions from the model or from a satellite-derived cloud type product might provide a more robust description of when enhancement might be anticipated at low-levels. This development might reduce the number of occasions when orographic corrections are applied to the background radar data but no enhancement is observed at the surface.

8 Conclusions

This study has provided an assessment of the performance of a physical modelling approach to compute orographic enhancements for correcting radar data in upland areas. The corrections have been extracted from the implementation of the Alpert and Shafir (1989) model currently used to compute orographic enhancements as part of the STEPS nowcasting system. The results have been compared with the performance of the current operational method based on applying orographic corrections based on the climatology derived by Hill (1983). The main conclusions which can be drawn from the statistical and case study analysis are summarised below.

The Alpert and Shafir (1989) physical model offers a practical approach to derive realistic orographic corrections.
Comparable performance of the STEPS implementation of the Alpert and Shafir (1989) model considered in this study with the current operational method across the Upper Exe and Upper Taff regions demonstrates the model to perform reasonably well in upwind slope regions of upland areas. Application of the Alpert and Shafir (1989) enhancements and the operational corrections to the background radar data both led to improved radar data quality in terms of reduced RMSF values in these regions. Although radar data quality was generally worse as a result of applying the STEPS implementation of the Alpert and Shafir (1989) model than achieved with the current operational method, the approach clearly shows potential for generating more realistic enhancements in light of future developments and tuning. The physical model approach would also operate in real-time and deliver consistent orographic correction fields across the radar domain and between the radar processing and nowcasting applications. The tests to modify the model parameters discussed in this study demonstrate that the approach can be readily tuned to produce more realistic corrections or adapted in light of developments to the input data or radar processing methods.

The STEPS implementation of the Alpert and Shafir (1989) model is not currently suitable for operational use.
This study has highlighted considerable errors which result from applying the STEPS implementation of the Alpert and Shafir (1989) model to radar data downwind of hills and mountains. The analysis of rainfall measurements at Capel Curig in the Upper Conwy region shows that the prediction of unrealistic rain shadow regions leads to gross under-estimation of surface rainfall using radar data. This situation requires correcting before the output from the STEPS orographic enhancement scheme can be considered for use to correct radar data operationally.

Tuning of the Alpert and Shafir (1989) model is required before improvements to radar data quality in upland areas can be realised.
The tests conducted in this study show that the Alpert and Shafir (1989) model output is particularly sensitive to the choice of tuning parameters used. Given the critical dependence of radar data quality in upland areas on the magnitude and distribution of orographic corrections, this sensitivity is likely to have a considerable impact on improving radar data quality in the future. The horizontal resolution of the terrain data used to compute the local slope in the model has been shown to be particularly important in producing realistic corrections. The implementation of the Alpert and Shafir (1989) model to use 2 km resolution terrain data in the STEPS system is considered to be the main factor contributing to the unrealistic rain shadow regions observed.

9 Recommendations

1) Investigate the impact of terrain resolution on the orographic enhancements computed by the Alpert and Shafir (1989) model. Tests are required to determine the most appropriate horizontal resolution required to compute local slopes and generate realistic orographic corrections. The computer processing required to run the model at higher resolution needs to be assessed. Should the required horizontal resolution lead to excessive computing processing, such that it is not practical to run the scheme in an operational environment, investigations are required to develop a correction algorithm which simulates the effect of sub-grid terrain variability on the orographic enhancement field.

2) Trial alternative implementations of the Alpert and Shafir (1989) physical model to investigate the optimal tuning parameters which produce best radar data quality over upland areas. The trial should include an investigation of the impact of the velocity scaling and cloud lifetime parameters on radar data quality.

3) If found to produce improvements to radar data quality, implement an optimised version of the Alpert and Shafir (1989) model operating at an appropriate horizontal resolution as part of the operational radar data processing chain to correct for the orographic enhancement process.

4) Assess the impact of developments to the orographic enhancement scheme on the performance of the STEPS and NIMROD nowcasting systems. In light of the results discussed in this study, a short-term solution to improve the horizontal resolution of the terrain used in the current implementation of the Alpert and Shafir (1989) model in STEPS may be necessary even before the results of more systematic studies of optimal performance are known.

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